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The Wide-Area Energy Storage and Management System – Battery Storage Evaluation

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July 2009

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The Wide-Area Energy Storage and Management System – Battery Storage Evaluation

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Abstract

This report presents the modeling approach, methodologies, and results of the sodium sulfur (NaS) battery evaluation study, which was conducted by the Pacific Northwest National Laboratory (PNNL) operated for the U.S. department of Energy by Battelle Memorial Institute for the California Institute for Energy and Environment (CIEE) and California Energy Commission (CEC).

The goal of this research is to investigate technical characteristics and economics of the NaS battery energy storage used for regulation and real-time dispatch (also called *load following*) services in the electricity market operated by the California Independent System Operator (CAISO). This report is part of the deliverables for Phase II of the Wide Area Energy Storage and Management System (WAEMS) project.

The tasks addressed in Phase II are as follow:

- Study the value of the ancillary services that can be provided by the NaS battery for the following two wind energy penetration scenarios: (1) a hypothetical scenario without wind energy resource and (2) a scenario with 20% of CAISO's energy supply being provided by renewable resources including the wind energy resource. Scenario (1) was analyzed to compare the incremental effects of wind power production.
- Evaluate technical and economical characteristics of the NaS battery when it is used to provide regulation and real-time dispatch services.
- Consider different operational conditions, find limitations, and recommend additional opportunities for the NaS battery arising in the California energy market.
- Suggest design improvements for the following NaS battery physical characteristics helping to increase the value and expand market opportunities in California: energy capacity, power output, and lifetime.

The results and conclusions of the study are summarized as follows:

- If an NaS battery is operated for 20 years at its rated output 4 MW, operating it at a lower depth of discharge (DOD) results in less cost with the now lifecycle-DOD curve. If manufacturers can improve the NaS battery lifecycles at high DODs, the breakeven prices will drop significantly for high DOD cases.
- Under the *pay-by-energy* scheme for regulation and real-time dispatch services, for a 4 MW, 28 MWh NaS battery to provide regulation and real-time dispatch services, breakeven prices are above 100 $/MWh, making the operation not economical in the California market.
- Under the *pay-by-capacity* scheme for regulation services, the battery has a longer life and a lower cost when it runs at lower DOD. With current technology, the battery rated power output is 4 MW. The results indicate that if the 4 MW battery provides one-directional regulation service, the high-end cost will be 26 $/MW and the low-end cost will be 16 $/MW. In the California market, this means the NaS battery may become marginally profitable.
- If the battery rated power can be increased, the breakeven price will drop significantly because the battery is able to handle a broader range of signals. However, after 12 MW, the price drop is not significant, but the battery life is shortened dramatically. Therefore, based on the current

lifecycle-DOD curve, it is beneficial for the battery manufacturer to increase the battery rated power output up to 8 or 12 MW, which will result in a breakeven price drop of 1/2 to 1/3.

- At higher-rated power, there is a tradeoff between the DOD and battery life. At 4 MW, the DOD does not result in a shortened battery life because the 28 MWh NaS battery is underused when providing the regulation. At 20 MW, however, the battery lives are significantly shorter at higher DODs.

- The NaS battery provides almost the same amount of regulation or real-time dispatch services for the "with 20% renewables" and "without wind" cases. Thus, the breakeven prices were similar. More batteries contribute greater ancillary service capacity and therefore, allow more intermittent generation resources to connect to the power grid. However, the amount of regulation and real-time dispatch services that an individual battery provides depends mainly on its power rating. For the "with 20% renewables" and "without wind" cases, signals sent to the NaS battery are all within its rated power output ±4 MW. For example, although 193 MW are needed for regulation without wind, and 248 MW are needed for regulation with 20% renewable, for the 4 MW NaS battery, it provides services within ±4 MW in both cases; therefore, the amounts of energy provided in both cases are similar.

- The NaS battery provides economical and reliable regulation and real-time dispatch services if it responds to a one-directional signal with small variations and close to the battery rated power output. For regulation signals outside the battery's capability, it is recommended that storage devices with high power outputs but less energy storage capacity such as flywheels provide the regulation service.

Executive Summary

This report presents the modeling approach, methodologies, and results of the sodium sulfur (NaS) battery evaluation study, which was conducted by the Pacific Northwest National Laboratory (PNNL) operated for the U.S. department of Energy by Battelle Memorial Institute for the California Institute for Energy and Environment (CIEE) and California Energy Commission (CEC).

Background

California has set the goal of reaching 20% renewable energy by 2012. Moving quickly towards this goal, the California Independent System Operator (CAISO) needs to find ways to mitigate the intermittence and fast-ramp that occurs at higher penetration levels of intermittent resources, the majority of which are wind and solar power. Pumped-hydro power plants, batteries, flywheels, distributed generation resources, and demand side management are flexible energy storage options that could potentially provide the needed fast responsive ancillary service resources. Pacific Gas and Electric (PG&E) is planning to build a 4 MW, 28 MWh NaS battery storage. To evaluate operational, market, and regulatory opportunities and limitations concerning the use of the PG&E Battery Storage Facility, PNNL proposed this research to CIEE and CEC.

Ford Motor Company pioneered the NaS battery in the 1960s to power early-model electric cars; NGK and Tokyo Electric refined it for the power grid. The benefits of the NaS battery are its high energy density, efficiency, and long-term durability [1][2]. For example, its energy density is approximately three times larger than lead-acid batteries. Furthermore, the battery can be charged and discharged over periods of 7 hours or stored indefinitely if the temperature is maintained at 600 degrees Fahrenheit. The cycle life of NaS batteries is based on depth of discharge and environmental factors. However, when a battery is providing regulation or real-time dispatch services, the battery capacity may not be fully used, resulting in a low utilization factor. Whether or not the services are economical is unknown. We expect that this research will lay a solid foundation for an extensive energy storage evaluation study, which will include the economics of all energy storage options for both the energy and ancillary services.

Objectives

The goal of this research is to investigate technical characteristics and economics of the NaS battery energy storage used for regulation and real-time dispatch (also called *load following*) services in the electricity market operated by the California Independent System Operator (CAISO). This report is part of the deliverables for Phase II of the Wide Area Energy Storage and Management System (WAEMS) project.

The tasks addressed in Phase I are as follow:

- Evaluate and compare available energy storage options. Review the world experience. Identify the top three technologies that can meet the needs of this project.
- Design and evaluate configurations and integration schemes of the energy storage, generation resources, their combinations, and other options. Identify the most promising configurations and their benefits.

- Analyze the technical and market compatibility of the proposed integration schemes with the existing regulation and load following systems at Bonneville Power Administration (BPA) and CAISO.
- Collect data needed for experiments at BPA and CAISO.
- Develop algorithms for the energy storage and generation control. Implement them as MATLAB™ codes.
- Conduct experiments using the MATLAB™ model and collected data.
- Carry out the cost benefit analyses based on simulation results.
- Provide a summary of results and recommendations for possible continuation of the project.

The tasks addressed in Phase II are as follow:

- Study the value of the ancillary services that can be provided by the NaS battery for the following two wind energy penetration scenarios: (1) a hypothetical scenario without wind energy resource and (2) a scenario with 20% of CAISO's energy supply being provided by renewable resources including the wind energy resource. Scenario (1) was analyzed to compare the incremental effects of wind power production.
- Evaluate technical and economical characteristics of the NaS battery when it is used to provide regulation and real-time dispatch services.
- Consider different operational conditions, find limitations, and recommend additional opportunities for the NaS battery arising in the California energy market.
- Suggest design improvements for the following NaS battery physical characteristics helping to increase the value and expand market opportunities in California: energy capacity, power output, and lifetime.

Approach

The modeling framework is shown in Figure 1. The regulation and real-time dispatch signals were simulated using 2006 CAISO historical data sets. The battery model was developed based on battery depth of discharge characteristics. The methodology used in Phase I of this project was improved by considering the physical characteristics of the NaS battery storage so that the number of battery lifecycles and annual energy provided are realistic. The battery performance was simulated by feeding the simulated minute-to-minute regulation and real-time dispatch signals into the battery model. To evaluate the efficacy of the NaS battery storage in mitigating the intermittence brought by the higher levels of penetration of renewable energy, a scenario was studied with 20% of the CAISO load being supplied by renewable energy resources including wind generation, and compared it against a scenario with zero wind generation.

To provide regulation or real-time dispatch service, an NaS battery can run at either the bi-directional or one-directional mode. In the bi-directional mode, the battery responds to both "up" and "down" signals. In the one-directional mode, the battery responds to the "up" signal when it is discharging and the "down" signal when charging. The one-directional operation scheme was selected and modeled in detail in this study because the one-directional operation allows the NaS battery to have a longer service life and is easier to implement compared to bi-directional operation schemes.

In the benefit study, the economics of the four services in terms of breakeven[1] costs were evaluated and compared for different device performance characteristics and operation mechanisms to find the best options. Net present value (NPV)[2] was not calculated because the service's breakeven costs were not low enough to provide a positive NPV given assumed CAISO market prices for regulation and real-time dispatch services. There were two sets of breakeven prices considered: the high-end cost and the low-end cost. The high-end cost was obtained by applying pessimistic estimations of input variables, and the low-end cost was obtained by applying the optimistic ones.

Two payment methods were studied for the regulation service: *pay-by-capacity* and *pay-by-energy*[3]. For the real-time dispatch service, only the *pay-by-energy* method was considered.

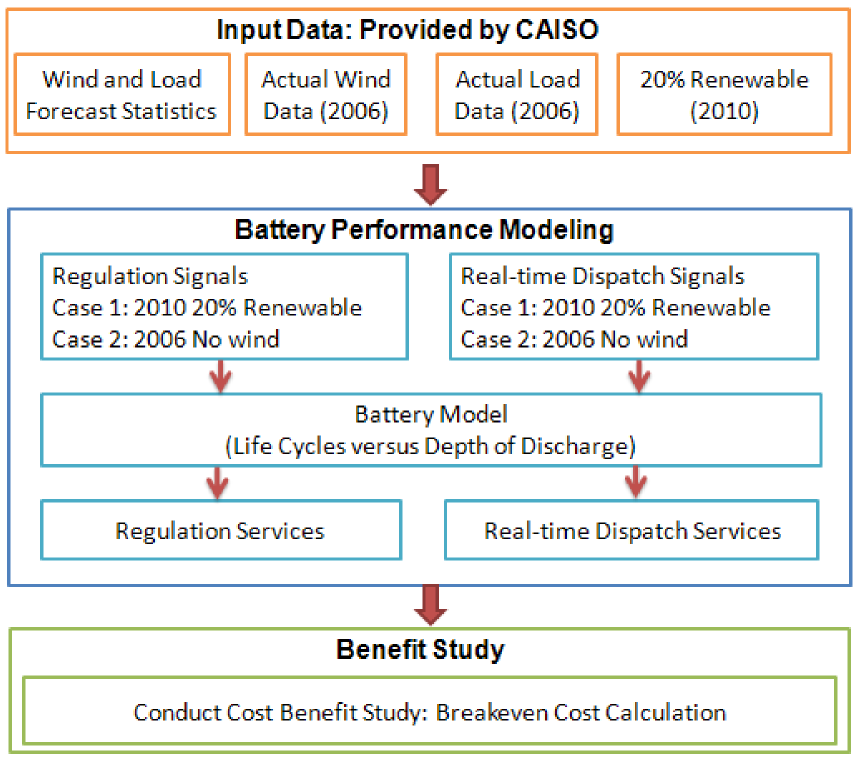


Figure 1: The modeling framework

Results and Conclusions

The modeling results are summarized in Table 1 to Table 3, which are color scaled for better visualization. The greener the color, the better the value. The results and conclusions of the study are summarized as follows:

- Improved lifecycles: If an NaS battery is operated for 20 years at its rated output, 4 MW, operating it at a lower depth of discharge (DOD) results in less cost with the current lifecycle-

[1] The break-even [3] point for a product is the point where total revenue received equals the total costs associated with the sale of the product.
[2] Net present value (NPV) or net present worth (NPW) [4] is defined as the total present value (PV) of a time series of revenues - costs.
[3] Pay-by-capacity means that a unit is paid by the capacity that it bids into the market regardless of the actual energy that it provides to the grid. Pay-by-energy means that a unit is paid by the actual energy that it provides to the grid.

DOD curve, as shown by the blue line in Figure 2. However, if manufacturers can improve the NaS battery's number of lifecycles at high DODs, as shown by the red line in Figure 2, the breakeven prices will drop significantly for high DOD cases. The results are compared in Figure 3 and Table 1.

- As shown in Table 2, under the *pay-by-energy* scheme for regulation and real-time dispatch services, for a 4 MW, 28 MWh NaS battery to provide regulation and real-time dispatch services, breakeven prices are above $100/MWh, making the operation not economical in the California market.

- As shown in Table 3, under the *pay-by-capacity* scheme for regulation services, the battery has a longer life and a lower cost when it runs at lower DOD. With current technology, the battery rated power output is 4 MW. The results indicate that if the 4 MW battery provides one-directional regulation service, the high-end cost will be $26/MW and the low-end cost will be $16/MW. In the California market, this means the NaS battery may become marginally profitable.

Table 1: The breakeven prices of two lifecycle-DOD curves

Base Case With current technology			High End Breakeven Price ($/MWh)		Low End Breakeven Price ($/MWh)	
Life	DOD	Life (cycle)	0% Profit	8% Profit	0% Profit	7% Profit
20	5%	379208	15.22	23.12	7.61	11.84
20	10%	125092	23.08	35.04	11.54	17.94
20	20%	41265	34.98	53.11	17.49	27.19
20	30%	21569	44.61	67.74	22.31	34.68
20	40%	13612	53.02	80.51	26.51	41.22
20	50%	9525	60.61	92.04	30.31	47.12
20	60%	7115	67.62	102.68	33.81	52.57
20	70%	5560	74.17	112.63	37.08	57.66
20	80%	4490	80.36	122.03	40.18	62.48
20	90%	3719	86.24	130.96	43.12	67.05
20	100%	3142	91.87	139.51	45.94	71.43
Technology Improvement Prolonged Lifecycles at Higher DODs			High End Breakeven Price ($/MWh)		Low End Breakeven Price ($/MWh)	
Life	DOD	Life (cycle)	0% Profit	8% Profit	0% Profit	7% Profit
20	5%	379208	15.22	23.12	7.61	11.84
20	10%	125092	23.08	35.04	11.54	17.94
20	20%	53645	26.91	40.86	13.45	20.92
20	30%	32354	29.74	45.16	14.87	23.12
20	40%	27224	26.51	40.25	13.25	20.61
20	50%	23813	24.24	36.82	12.12	18.85
20	60%	21345	22.54	34.23	11.27	17.52
20	70%	19460	21.19	32.18	10.60	16.48
20	80%	17960	20.09	30.51	10.05	15.62
20	90%	16736	19.17	29.10	9.58	14.90
20	100%	15710	18.37	27.90	9.19	14.29

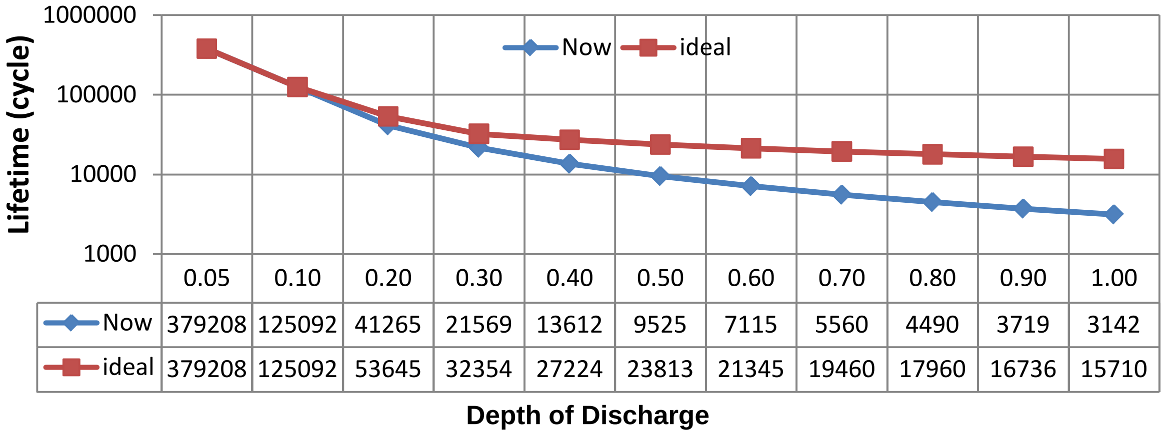
Table 2: The breakeven prices, utilization rates, and battery lifetimes (Pay-by-energy)

		Breakeven Price (8% Profit) ($MWh)					Utilization Rate (P_{ave}/P_{rated})					Adjusted LifeTime (Year)				
	P_{rated} (MW)	DOD					DOD					DOD				
		1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation 20% Renewables	4	197	206	204	198	238	0.18	0.17	0.17	0.18	0.15	20	20	20	20	20
	8	112	106	103	119	124	0.18	0.18	0.17	0.15	0.14	14	16	20	20	20
	12	89	89	86	80	87	0.18	0.16	0.15	0.15	0.13	10	12	15	20	20
	16	84	79	73	67	68	0.15	0.15	0.15	0.14	0.13	8	10	12	15	20
	20	77	71	65	60	57	0.15	0.15	0.15	0.14	0.12	7	8	9	13	20
Real-time Dispatch 20% Renewables	4	164	169	183	203	270	0.15	0.15	0.14	0.12	0.09	20	20	20	20	20
	8	97	101	114	135	189	0.13	0.12	0.11	0.09	0.07	19	20	20	20	20
	12	82	83	90	108	148	0.11	0.10	0.09	0.08	0.06	15	19	20	20	20
	16	74	73	77	95	125	0.10	0.09	0.08	0.07	0.05	13	16	20	20	20
	20	68	68	70	83	110	0.09	0.08	0.07	0.06	0.05	11	14	19	20	20
Regulation No-wind	4	135	137	137	135	144	0.18	0.18	0.18	0.18	0.17	20	20	20	20	20
	8	77	73	71	72	79	0.18	0.18	0.18	0.17	0.16	14	16	19	20	20
	12	63	60	55	52	55	0.18	0.17	0.17	0.16	0.15	9	11	13	18	20
	16	56	52	48	45	43	0.17	0.17	0.17	0.16	0.14	7	8	10	14	20
	20	52	48	44	40	37	0.17	0.17	0.16	0.16	0.14	6	7	8	11	19
Real-time Dispatch No-wind	4	177	179	201	229	303	0.14	0.14	0.12	0.11	0.08	20	20	20	20	20
	8	108	115	128	151	219	0.12	0.11	0.10	0.08	0.06	20	20	20	20	20
	12	86	90	101	121	172	0.10	0.09	0.08	0.07	0.05	16	20	20	20	20
	16	77	79	87	109	147	0.09	0.08	0.07	0.06	0.04	14	17	20	20	20
	20	72	74	78	96	129	0.08	0.07	0.06	0.05	0.04	12	16	20	20	20

Table 3: The breakeven price comparison between pay-by-energy and pay-by-capacity

		High-end Pay-by-**Capacity** ($/MW)					Low-end Pay-by-**Capacity** ($/MW)					**Adjusted Life Time (Year)**				
	P_{rated} (MW)	**DOD**					**DOD**					**DOD**				
		1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation	**4**	26	26	26	26	26	16	16	16	16	16	20	20	20	20	20
	8	15	14	13	13	13	9	9	8	8	8	14	16	20	20	20
20%	**12**	12	10	10	9	9	8	7	6	5	5	10	12	15	20	20
Renewables	**16**	10	9	8	7	7	6	6	5	4	4	8	10	12	15	20
	20	9	8	7	6	5	6	5	5	4	3	7	8	9	13	20
Regulation	**4**	26	26	26	26	26	16	16	16	16	16	20	20	20	20	20
No-wind	**8**	15	14	13	13	13	9	9	8	8	8	14	16	19	20	20
	12	12	11	10	9	9	8	7	6	6	5	9	11	13	18	20
	16	10	10	9	7	7	7	6	6	5	4	7	8	10	14	20
	20	9	9	8	7	5	6	6	5	4	3	6	7	8	11	19

		High-end Pay-by-**Energy** ($/MWh)					Low-end Pay-by-**Energy** ($/MWh)					**Adjusted Life Time (Year)**				
	P_{rated} (MW)	**DOD**					**DOD**					**DOD**				
		1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation	**4**	197	206	204	198	238	86	90	89	86	104	20	20	20	20	20
	8	112	106	103	119	124	50	47	45	52	54	14	16	20	20	20
20%	**12**	89	89	86	80	87	41	40	38	35	38	10	12	15	20	20
Renewables	**16**	84	79	73	67	68	39	37	33	30	30	8	10	12	15	20
	20	77	71	65	60	57	37	33	30	27	25	7	8	9	13	20
Regulation	**4**	135	137	137	135	144	83	84	84	83	88	20	20	20	20	20
No-wind	**8**	77	73	71	72	79	49	46	44	44	48	14	16	19	20	20
	12	63	60	55	52	55	41	39	35	32	34	9	11	13	18	20
	16	56	52	48	45	43	37	34	31	28	27	7	8	10	14	20
	20	52	48	44	40	37	35	32	29	25	23	6	7	8	11	19



	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Now	379208	125092	41265	21569	13612	9525	7115	5560	4490	3719	3142
ideal	379208	125092	53645	32354	27224	23813	21345	19460	17960	16736	15710

Figure 2: The battery lifetime with respect to the depth of discharge

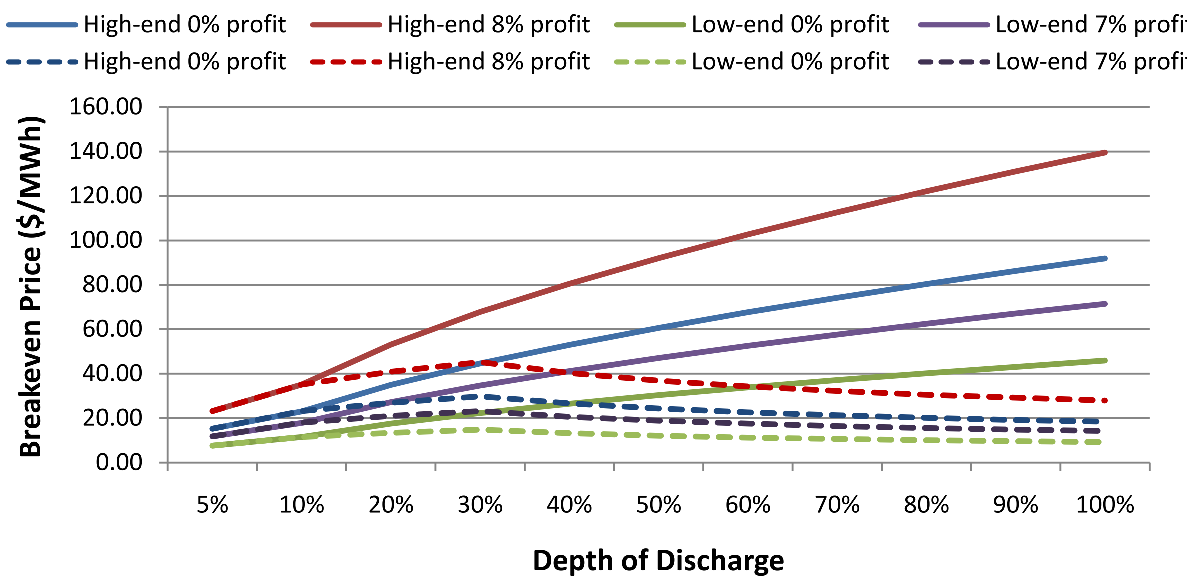


Figure 3: A comparison of high-end and low-end breakeven prices of the improved battery lifecycle case (dash-lines) and the base case (solid lines)

- As shown in Table 2 and Table 3, if the battery rated power can be increased (as shown in Figure 4), the breakeven price will drop significantly because the battery is able to handle a broader range of signals. However, after 12 MW, the price drop is not significant, but the battery life is shortened dramatically. Therefore, based on the current lifecycle-DOD curve, it is beneficial for the battery manufacturer to increase the battery rated power output up to 8 or 12 MW, which will result in a breakeven price drop of 1/2 to 1/3.

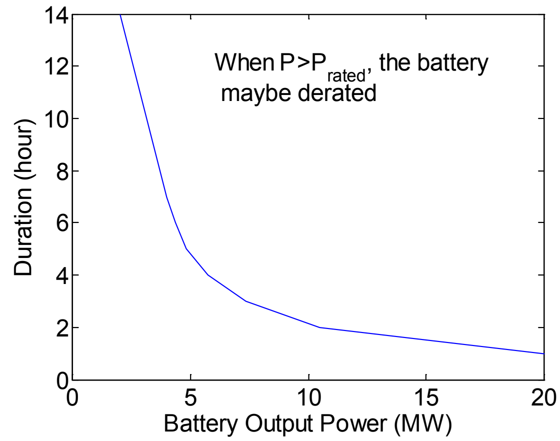


Figure 4: The 28 MWh NaS battery capacity to power ratio

- As also shown in Table 2 and Table 3, at higher-rated power, there is a tradeoff between the DOD and battery life. At 4 MW, the DOD does not result in a shortened battery life because the 28 MWh battery is underused when providing the regulation service. At 20 MW, however, the battery lives are significantly shorter at higher DODs.

- The NaS battery provides almost the same amount of regulation or real-time dispatch services for the "with 20% renewables" and "without wind" cases. Thus, the breakeven prices were similar. More batteries contribute greater ancillary service capacity and therefore, allow more intermittent generation resources to connect to the power grid. However, the amount of regulation and real-time dispatch services that an individual battery provides depends mainly on its power rating. For the "with 20% renewables" and "without wind" cases, signals sent to the NaS battery are all within its rated power output ±4 MW. For example, although 193 MW are needed for regulation without wind, and 248 MW are needed for regulation with 20% renewable, for the 4 MW NaS battery, it provides services within ±4 MW in both cases; therefore, the amounts of energy provided in both cases are similar.

- The regulation and real-time dispatch signals sent to the NaS battery are scaled total regulation and real-time dispatch signals, so that the signals are within the battery rated power output, for example, ±4 MW. As shown in Figure 5, for the case in which 50% of the time, the normalized signal is outside ±4MW, the battery average power output is much higher than that of the 5% case, resulting in more economical services, as shown in Table 4. For the 50% of signals outside the battery's capability, storage devices with high power outputs but less energy storage capacities, such as a flywheel, would be better suited to provide the regulation and real-time dispatch signals.

Future research should focus on the economics of the combined services of batteries. By providing services to the energy, regulation, real-time dispatch, and reserve markets, the battery owner can collect revenue from different markets, resulting in a more economical operation than bidding in a single market. However, providing multiple services requires an optimization of the battery's commitment schedule. To address these optimal operation strategies, a battery commitment problem needs to be well defined and solved.

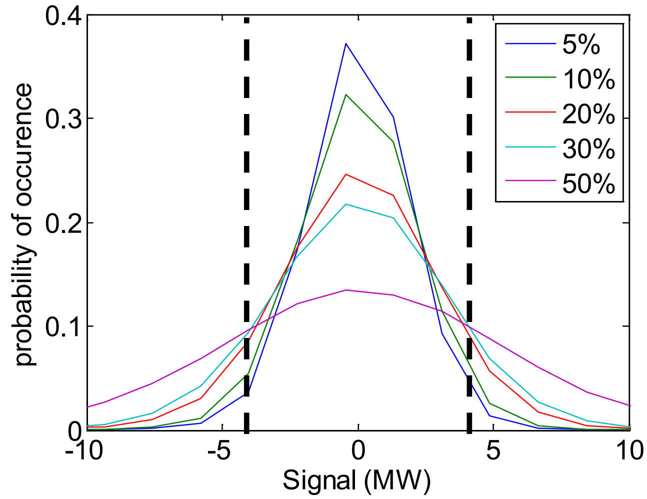


Figure 5: The probability distribution functions of the regulation signals

Table 4: A comparison of breakeven prices for different normalized signals

		Breakeven Price (High End)					Breakeven Price (Low End)				
	Signal	DOD					DOD				
	Outliers	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation	5%	197	206	204	198	238	101	105	104	101	122
	10%	175	177	176	171	203	90	90	90	87	104
20%	20%	138	140	135	148	160	71	72	69	76	82
Renewables	30%	131	129	127	143	146	67	66	65	73	75
	50%	112	105	101	112	116	59	55	52	57	60
Realtime	5%	231	238	257	285	381	118	122	132	146	195
Dispatch	10%	205	217	228	270	355	105	111	117	138	182
	20%	174	181	195	231	308	89	93	100	118	158
20%	30%	151	159	177	204	278	77	82	91	104	142
Renewables	50%	135	142	155	180	239	70	73	79	92	123
Regulation	5%	191	193	193	190	202	98	99	99	97	104
No-wind	10%	175	172	175	172	185	90	88	89	88	95
	20%	144	144	143	149	156	74	74	73	76	80
	30%	132	131	129	140	144	68	67	66	72	74
	50%	117	112	108	113	119	61	58	55	58	61
Realtime	5%	249	251	283	322	426	128	129	145	165	218
Dispatch	10%	217	226	254	285	387	111	116	130	146	198
No-wind	20%	183	201	219	250	339	94	103	112	128	174
	30%	167	183	193	224	312	86	94	99	115	160
	50%	143	147	161	192	267	73	75	82	98	137

Acknowledgment

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Nomenclature

ACE	Area control error (MW)
I_a	Net interchange (MW)
I_s	Scheduled net interchange (MW)
B	Area frequency bias constant
F_a	Actual frequency (Hz)
F_s	Scheduled frequency (Hz)
G_{ha}	Hour-ahead generation schedule (MW)
G_s	Scheduled generation (MW)
G_a	Actual generation (MW)
G_{ha}^w	Hour-ahead wind generation (MW)
G^r	Regulation (MW)
G^{lf}	Load following (MW)
G^w	Wind generation (MW)
ΔG^{ud}	Total deviation of generation from the dispatched instructions (MW)
ΔG^w	Wind generation real-time schedule forecast error (MW)
ΔG^{lf}	The deviation of the load following unit from its base point (MW)
ΔG^r	The deviation of the regulation unit from its base point (MW)
L_{ha}	Hour-ahead load (MW)
L_a	Actual load (MW)
$G_{rtf,5\min}^{w,y}$	5-minute short-term forecasts of wind generation (MW)
$L_{rtf,5\min}^{y}$	5-minute short-term forecasts of load (MW)
P_{rated}	Battery rated power (MW)
P_{ave}	Battery average power output (MW)
E_B	Battery rated capacity (MWh)
L_c	Life (cycle)
L_y	Life (year)
n_y	Number of cycles in a year
n_h	Number of cycles in an hour
k_{DOD}	Depth of discharge (DOD)
K_u	Utilization factor

η	Efficiency
E_{life}	Lifetime energy (MWh)
E_{Annual}	Annual energy (MWh)
B_{BE}	Breakeven price ($/MW)
R	Revenue ($)
$C_{install}$	Installation cost ($/kW)
C_{cap}	Capital cost ($)
k_{op}	Operation cost factor
C_{op}	Operation cost ($)
C	Total op+cap
π	Profit
NPV	Net present value ($)
R_{yr}	Annual benefit ($)
C_{yr}	Annual levelized cost ($)
i	Discount rate
n	Plant life in years

Contents

List of Tables

List of Figures

1.0 Introduction

This document describes the approach and results developed by the Pacific Northwest National Laboratory (PNNL) and used in evaluating the 4 MW, 28 MWh sodium sulfur (NaS) battery under a contract with the California Institution for Energy and Environment (CIEE). The project has been funded by the California Energy Commission (CEC). In this report, the motivation, objectives, and benefits of the research are discussed. Next, the scope of the project is outlined, and finally, results and conclusions are provided.

1.1 Background

California has set the goal of reaching 20% renewable energy by 2012. Moving quickly towards this goal, the California Independent System Operator (CAISO) needs to find possible means to mitigate the intermittence and fast-ramp that occurs at higher penetration levels of intermittent resources, the majority of which are wind and solar power. Pumped-hydro power plants, batteries, flywheels, distributed generation resources, and demand side management are flexible energy storage options that could potentially provide the needed fast responsive ancillary service resources. Pacific Gas and Electric (PG&E) is planning to build a 4 MW, 28 MWh NaS battery storage. To evaluate operational, market, and regulatory opportunities and limitations concerning the use of the PG&E Battery Storage Facility, PNNL proposed this research to CIEE and CEC.

Ford Motor Company pioneered the NaS battery in the 1960s to power early-model electric cars; NGK and Tokyo Electric refined it for the power grid. The benefits of the NaS battery are its high energy density, efficiency, and long-term durability [1][2]. For example, its energy density is approximately three times larger than lead-acid batteries. Furthermore, the battery can be charged and discharged over periods of 7 hours or stored indefinitely if the temperature is maintained at 600 degrees Fahrenheit. The cycle life of NaS batteries is based on depth of discharge and environmental factors. However, when a battery is providing regulation or real-time dispatch services, the battery capacity may not be fully used, resulting in a low utilization factor. Whether or not the services are economical is unknown. We expect that this research will lay a solid foundation for an extensive energy storage evaluation study, which will include the economics of all energy storage options for both the energy and ancillary services.

To accept and accommodate the ancillary services provided by those devices in the CAISO market, CAISO needs answers to the following questions:

- What is the quantity (in terms of the downward and upward power capacity and energy) and quality (in terms of the availability, flexibility, ramping capability, ramp duration capability, etc.) of the ancillary service that an energy storage device can provide?
- Will the services provided be economically justified? What needs to be done to make them economical?
- What are the existing market opportunities for energy storage providers in the California market? Is there a need to introduce changes to the existing market rules and/or to the operating procedures in California to make the use of energy storage resources more cost effective and beneficial to grid reliability?

- What are the desired device performance characteristics for energy storage devices needed to provide more valuable ancillary services to the grid? The answer to this question could provide design guidance for the battery manufacturers and designers.

Motivated by CAISO's needs, CEC (Mike Gravely) proposed this battery storage evaluation study. Because of funding limitations, the scope was limited to evaluating the economics and performance of an existing 4 MW NaS battery energy storage device while performing regulation and real-time dispatch services in the electricity markets operated by CAISO.

1.2 Objectives

The goal of this research is to investigate technical characteristics and economics of the NaS battery energy storage used for regulation and real-time dispatch (also called *load following*) services in the electricity market operated by the California Independent System Operator (CAISO). This report is part of the deliverables for Phase II of the Wide Area Energy Storage and Management System (WAEMS) project.

The tasks addressed in Phase I are as follow:

- Evaluate and compare available energy storage options. Review the world experience. Identify top three technologies that can meet the needs of this project.
- Design and evaluate configurations and integration schemes of the energy storage, generation resources, their combinations, and other options. Identify the most promising configurations and their benefits.
- Analyze technical and market compatibility of the proposed integration schemes with the existing regulation and load following systems at BPA and CAISO.
- Collect data needed for experiments at BPA and CAISO.
- Develop algorithms for the energy storage and generation control. Implement them as MATLAB™ codes.
- Conduct experiments using the MATLAB™ model and collected data.
- Carry out the cost benefit analysis based on simulation results.
- Provide a summary of results and recommendations for possible continuation of the project.

The tasks addressed in Phase II are as follow:

- Study the value of the ancillary services that can be provided by the NaS battery for the following two wind energy penetration scenarios: (1) a hypothetical scenario without wind energy resource and (2) a scenario with 20% of CAISO's energy supply being provided by renewable resources including the wind energy resource. Scenario (1) was analyzed to compare the incremental effects of wind power production.
- Evaluate technical and economical characteristics of the NaS battery when it is used to provide regulation and real-time dispatch services.
- Consider different operational conditions, find limitations, and recommend additional opportunities for the NaS battery arising in the California energy market.

- Suggest design improvements for the following NaS battery physical characteristics helping to increase the value and expand market opportunities in California: energy capacity, power output, and lifetime.

1.3 Scope of Work

The original scope of work is listed as follows:

- Evaluate operational, market, and regulatory opportunities and limitations concerning the use of the Pacific Gas and Electric (PG&E) Battery Storage Facility.
- Identify and analyze potential uses of the sodium sulfur energy storage facility that include peak shaving, intraday energy storage, black start applications, wind and solar generation intermittency mitigation, regulation, real-time dispatch, voltage support, stability enhancement, frequency response, and other potential uses.
- Analyze market and operational conditions, limitations, and opportunities associated with each potential application for NaS battery storage. Determine whether the battery's physical characteristics such as the size, energy capacity, cycling capacity, lifetime, and others can appropriately support (economically, etc.) the intended application.
- Identify what changes might be needed in CAISO's market (operating procedures and practices, control systems) Federal Energy Regulatory Commission (FERC) regulations or North American Reliability Corporation (NERC)/Western Electricity Coordinating Council (WECC) standards to create feasible, economic applications for the NaS battery storage.
- Provide a summary report addressing each of the above bulleted points.

On April 10, 2009, a discussion with Mike Gravely (CEC) was followed by a number of phone interviews with Dave Hawkins (CAISO) and Jon Eric Thalman (PG&E). Based on Mike Gravely's recommendations and a consensus from the CIEE project managers, to address changes in research needs, the scope of work was revised slightly as follows:

Evaluate operational and market opportunities and limitations concerning the use of PG&E Battery Storage Facility (4 MW, 28 MWh).

- Analyze the market and operational conditions, limitations, and opportunities for real-time dispatch for NaS battery storage in conjunction with wind and solar generation intermittency. Determine lifecycle costs and NPV under CAISO conditions associated with renewable energy penetration at 33% of total supply.
- Determine whether the battery's performance envelope (physical) characteristics such as the size, energy capacity, cycling capacity, lifetime, and others, can appropriately support (based on economics and technical characteristics) the intended application.
- Update Phase I NaS battery evaluation with regard to regulation within the market redesign and technology upgrade (MRTU) pricing schedule. Update Phase I NPV methodology to evaluate CAISO regulation with CAISO simulation data.
- Identify what changes might be needed in California's market (operating procedures and practices, control systems) FERC regulations or NERC/WECC standards to create feasible, economic application associated real-time dispatch and regulation for the NaS battery storage. If time and money permit, evaluate changes required for regulation using the NaS battery.

There were three minor changes to the revised scope when we conducted this study:

- Because there was no active non-disclosure agreement (NDA) with CAISO in place, we couldn't obtain planning data for 33% renewable penetration from CAISO. Therefore, in this study, we used regulation and real-time dispatch signals generated in Phase I for 20% renewables penetration.
- Net present value (NPV) was not calculated because this study only evaluated the battery for each service separately, and neither of the service's breakeven prices (costs) were low enough to provide a positive net present value given assumed CAISO prices for regulation and real-time dispatch services.
- Market rules for battery storage devices to bid into ancillary service markets were under development at the time when this research was conducted. Therefore, suggestions for rule changes are not provided.

2.0 Modeling Approach

The modeling framework is shown in Figure 6. The regulation and real-time dispatch signals were simulated using 2006 CAISO historical data sets. The battery model was developed based on battery depth of discharge characteristics. The methodology used in Phase I of this project was improved by considering the physical characteristics of the NaS battery storage so that the number of battery lifecycles and annual energy provided are realistic. The battery performance was simulated by feeding the simulated minute-to-minute regulation and real-time dispatch signals into the battery model. To evaluate the efficacy of the NaS battery storage in mitigating the intermittence brought by the higher levels of penetration of renewable energy, a scenario was studied with 20% of the CAISO load being supplied by renewable energy resources including wind generation, and compared it against a scenario with zero wind generation.

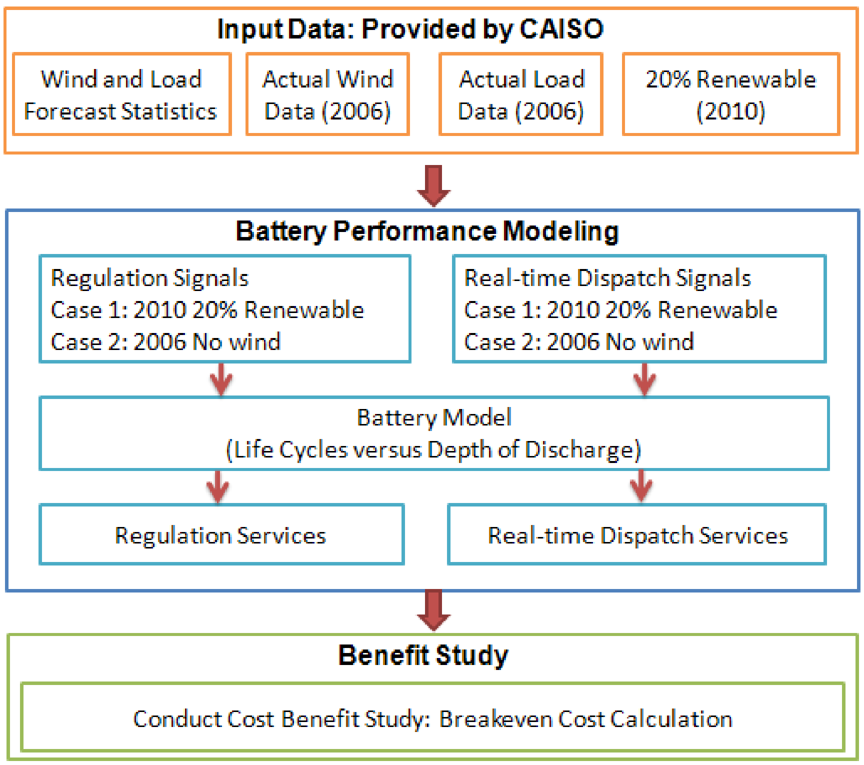


Figure 6: The modeling framework

To provide regulation or real-time dispatch service, an NaS battery can run at either the bi-directional or one-directional mode. In the bi-directional mode, the battery responds to both "up" and "down" signals. In the one-directional mode, the battery responds to the "up" signal when it is discharging and the "down" signal when charging. The one-directional operation scheme was selected and modeled in detail in this study. This is because the one-directional operation allows the NaS battery to have a longer service life and is easier to implement compared with bi-directional operation schemes.

In the benefit study, the economics of the four services in terms of breakeven[1] costs were evaluated and compared for different device performance characteristics and operation mechanisms to find the best options. Net present value (NPV)[2] was not calculated because the service's breakeven prices were not low enough to provide a positive NPV given assumed CAISO market prices for regulation and real-time dispatch services. There were two sets of breakeven prices considered: the high-end cost and the low-end cost. The high-end cost was obtained by applying pessimistic estimations of input variables, and the low-end cost was obtained by applying the optimistic ones.

Two payment methods were studied for the regulation service: pay-by-capacity and pay-by-energy[3]. For the real-time dispatch service, we only considered the pay-by-energy method.

2.1 Regulation and Real-time Dispatch Signal Generation

The algorithm used to generate regulation and real-time dispatch signals was developed in previous research. For detailed information, please refer to [5] and [6].

2.1.1 Area Control Error

The CAISO's operations control objective is to minimize its area control error (ACE) [5] to the extent sufficient to comply with the NERC Control Performance Standards. Therefore, the "ideal" regulation/real-time dispatch signal is the signal that opposes deviations of ACE from zero when it exceeds a certain threshold:

$$\begin{aligned} -ACE &= -(I_a - I_s) + \underbrace{10B(F_a - F_s)}_{Neglected} \\ &\approx G_s - L_s - G_a + L_a \rightarrow \min \end{aligned} \tag{1}$$

where I_a denotes net interchange (MW flow out of the control area); I_s refers to scheduled net interchange; B is area frequency bias constant; F_a and F_s are actual and scheduled frequency, respectively. Impacts of wind generation on the interconnection frequency are not modeled. This is a valid assumption given the large interconnection (>140GW peak load) whose frequency deviates very slightly with normal imbalances and that is maintained by several balancing authorities. The generation component of the ACE equation can be represented as follows:

$$G_s = G_{ha} + G_{ha}^{w} \tag{2}$$

$$G_a = G_s + \Delta G^{lf} + \Delta G^{r} + \Delta G^{w} + \Delta G^{ud} \tag{3}$$

where *ha* denotes the hour-ahead generation schedule; *lf* denotes instructed deviations from the hour-ahead schedule caused by generators involved in the real-time dispatch process; *r* denotes instructed deviations caused by generators involved in the regulation process, ΔG^{lf} and ΔG^{r} are the deviations of the

[1] The break-even point [4] for a product is the point where total revenue received equals the total costs associated with the sale of the product.
[2] Net present value (NPV) or net present worth (NPW) [1] is defined as the total present value (PV) of a time series of revenues - costs.
[3] Pay-by-capacity means that a unit is paid by the capacity that it bids into the market regardless of the actual energy that it provides to the grid. Pay-by-energy means that a unit is paid by the actual energy that it provides to the grid.

regulation and real-time dispatch units from their base points, ΔG^{w} is the deviation of the wind generators from their schedule (wind generation real-time schedule forecast error), and ΔG^{ud} is the total deviation of generators from the dispatched instructions. ΔG^{ud} is simulated similarly to the load forecast error (random number generator based on truncated normal distriution).

The total deviation of generators from dispatch instructions for conventional units that are not involved in regulation and real-time dispatch can be represented as follows:

$$\Delta G^{ud} = G_a - G_{ha} \tag{4}$$

$$\Delta G^{w} = G_a^{w} - G_{ha}^{w} \tag{5}$$

$$\Delta L = L_a - L_{ha}. \tag{6}$$

Because the control objective is $ACE \rightarrow 0$, Equation (1) can be rewritten as:

$$\Delta G^{lf} + \Delta G^{r} = \Delta L - \Delta G^{w} - \Delta G^{ud} \tag{7}$$

where ΔL is the deviation of the actual load from its real-time scheduled value (load forecast error).

Equation (7) is written for instantaneous values of ΔL, ΔG^{w}, and ΔG^{ud}. Therefore, the statistical interaction between the load forecast error and the wind generation forecast error is fully preserved in Equation (7). The load and wind generation errors can vary depending on the wind generation penetration level within the CAISO control area and the accuracy of the load forecast compared with the accuracy of the wind generation forecast. Because the percent wind generation forecast error is more significant than the percent load forecast error, the former may have a considerable impact on $\Delta G^{lf} + \Delta G^{r}$.

Wind generation would have no impact on regulation and real-time dispatch requirements if

$$\Delta G^{w} = 0. \tag{8}$$

By substituting Equation (8) into (7), we have

$$\Delta G^{rlf} = \Delta G^{lf} + \Delta G^{r} = \Delta L - \Delta G^{ud} \tag{9}$$

2.1.2 Separating Regulation and Real-time Dispatch

Real-time dispatch is understood as the difference between the hourly energy schedule including 20-minute ramps (shown as the red line) and the short-term 5-minute forecast/schedule and applied “limited ramping capability” function (blue line). This difference is also shown as the blue area below the curves. *Regulation* is interpreted as the difference between the actual CAISO generation requirement and the short-term 5-minute dispatch shown in Figure 7, as the red area between the blue and green lines.

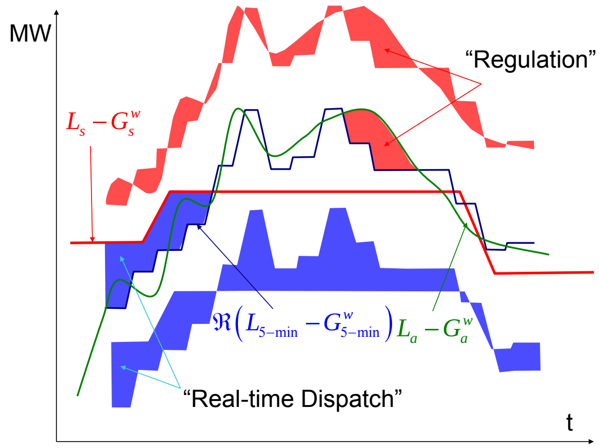


Figure 7. Separation of regulation from real-time dispatch based on simulated hour-ahead schedule

By simulating hour-ahead and 5-minute schedules for load and hour-ahead schedules for wind generation, regulation can be separated from real-time dispatch. The schedule/forecast based approach uses the short-term forecasts of wind generation and load, $G_{rtf,5\min}^{w,y}$ and $L_{rtf,5\min}^{y}$. In this case, the following formulas can be used:

$$\Delta G^r(m) = L_a^y(m) - G_a^{w,y}(m) - L_{rtf,5\min}^y(m) + G_{rtf,5\min}^{w,y}(m) \tag{10}$$

$$\Delta G^{lf}(m) = L_{rtf.5\min}^y(m) - G_{rtf,5\min}^{w,y}(m) - L_{rtf,1hr}^y(m) + G_{ha,1hr}^{w,y}(m) \tag{11}$$

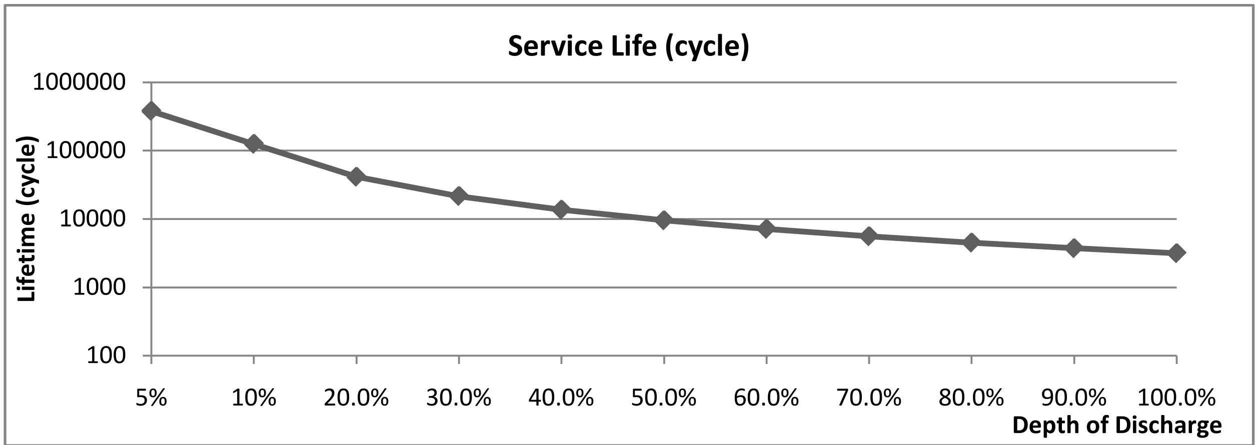
2.2 The Modeling of the NaS Battery Performance

2.2.1 Assumptions

The following assumptions have been made:

- Because this study focuses on the regulation and real-time dispatch services, it is assumed that the NaS battery is always in an "on" state, either charging or discharging. Therefore, neither start-up nor shut-down costs are considered in this cost calculation.

- Within the battery rated power output, the battery is able to ramp up and ramp down to any power output in milliseconds as often as required without shortening its lifecycles. There are two implications from this assumption. First, the battery can provide perfect regulation and real-time dispatch services without ramp rate concerns. Second, as long as the battery power output is within its rating, the only factor that drives the battery lifetime is the depth of discharge (DOD), as shown in Figure 8.



Depth of Discharge	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Life (Cycles)	379208	125092	41265	21569	13612	9525	7115	5560	4490	3719	3142

Figure 8: The battery lifetime with respect to the depth of discharge [7]

- It is also assumed that variation of power outputs will not negatively influence the battery life. For example, the life of an NaS battery charging/discharging at a constant power output of 2 MW (Figure 9: blue line) and the life of another NaS battery charging/discharging at variable power outputs with an average of 2 MW (Figure 9: purple line) will have the same lifetime. This is an optimistic assumption because there will be more wear and tear of the battery and its power electronics when batteries are frequently charging or discharging at variable power outputs than when they are charging/discharging at constant power output. However, the statistics for such lifetime reduction are not available. Because all cases in this study have been modeled under the same assumption, the results should be comparable.

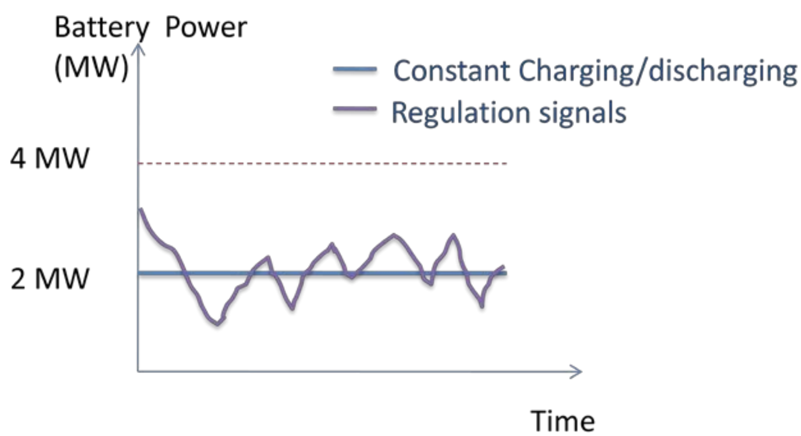


Figure 9: Battery output powers

- The speed of completing a charging and discharging cycle has no negative impact on the battery life. As shown in Figure 10, the wear and tear of a cycle completed in 14 hours is equivalent to a cycle completed in 30 hours. Because the battery life is counted by number of cycles, the longer a cycle is completed, the longer the battery life is. This optimistic assumption may result in a non-realistic battery life, such as 100 years. For example, as shown in Figure 8, the battery life is determined by the number of cycles with respect to different DODs. Assume that a battery is used for 100 cycles per year at 100% DOD. By calculation, the battery lifetime is 31.42 years, which is much longer than the 12 to 20 years service life documented so far. Therefore, we have capped the maximum service life of a battery to be 20 years to make our economic analysis realistic.

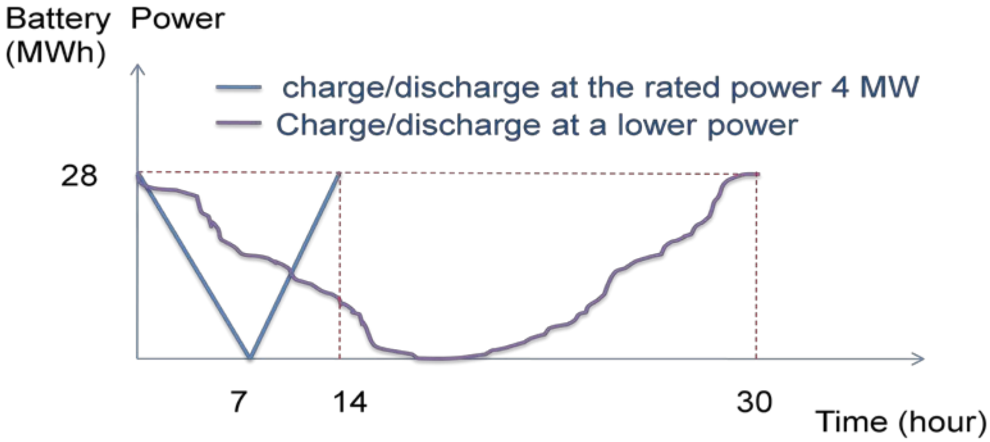


Figure 10: The charging/discharge profiles of an NaS battery

- The maximum service life of a battery is assumed to be 20 years to make our economic analysis realistic. In our simulation, the calculated lifetime may exceed 20 years.

- To address the influence of different power-capacity ratios, it is assumed that the rated power outputs of the NaS battery can reach 20 MW. The NaS battery that PG&E plans to install has a capacity of 28 MWh and rated power output at 4 MW. A 20 MW may not be achievable for current battery technology. However, we want the sensitivity study to provide battery manufacturers a reasonable estimate on how much improvement in the battery is required to provide the regulation and real-time dispatch services.

Table 5: NaS battery characteristics

NaS Battery Characteristics		Assumptions	Note
Battery Capacity (MWh)		28	
Battery Power (MW)		4	
Battery Life (year)		No more than 20	Varies between 12~20
General	**Self Discharging**	None	
	Efficiency	75-90%	75-90%
	Weight (MWh/kg)	110 MWh/kg	
	Depth of Discharge (DOD)	20% - 100%	
Cost	**Installation Cost ($/kWh)**	200	150 - 300
	Start-up Cost	Not included in the study	
	Shut-down Cost	Not included in the study	
	Operation Cost ($)	3% of capital cost	
Operation	**UP (Discharge)**	Ramp-up time in ms	May be limited
	DOWN (Charge)	Ramp-down time in ms	May be limited
	Cold Start (sec)	Always on (No cold start)	
	Shut-down Time	Always on (No shut-down)	

2.2.2 Normalization of the Regulation and Real-time Signals

The 2012 regulation and real-time dispatch signals for 20% renewables and no wind cases are generated from 2006 CAISO data sets using methodology described in Section 2.1. As shown in Figure 11 and Figure 12, the regulation and real-time signals of the 20% renewables case have larger magnitudes than those of the no wind case. The generated signals are total CAISO regulation or real-time dispatch signals and are too big for the NaS battery. Therefore, these signals need to be normalized first, so that the normalized control signals sent to the battery will be mostly within the battery rated power output, P_{rated}.

Based on the probability distribution functions (PDFs) shown in Figure 11 and Figure 12, assuming the battery is required to respond to 95%, 90%, 80%, and 50% control signals, values to normalize the total regulation and real-time dispatch signals to 1 MW are calculated, as shown in Table 6. To give a better illustration, cumulative density functions (CDFs) of the regulation and real-time dispatch are plotted in Figure 13 and Figure 14. As illustrated in these two figures, if we normalized the total control signals by the values highlighted in red in Table 6, then 80% signals are in the boxes and 20% signals are outside the boxes. Note that there may be more outliers on one side than another.

The average battery power output P_{ave} can be calculated by

$$P_{ave} = \frac{\sum_{t=1}^{N} \frac{P_{gs}}{P_{norm}}}{N} \tag{12}$$

where

P_{ave} The average battery power output (MW)

P_{gs} The generated signal magnitude (MW)

P_{norm} The value used to normalize the generated signals (MWh)

t Time (minute)

N The number of minutes that the battery operates in 1 year

Equation (12) indicates that a smaller P_{norm} results in a greater P_{ave}. This implies that if the battery does not respond to extreme regulation and real-time signals, it will run at a higher average output than otherwise.

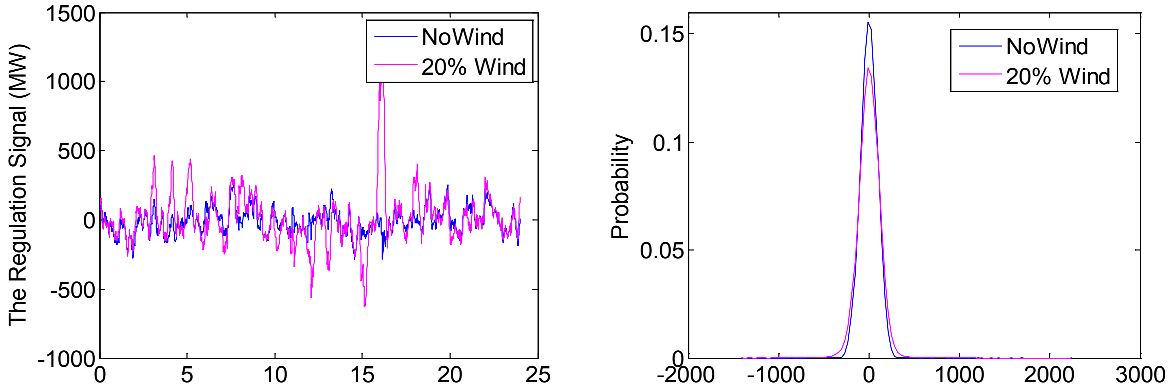


Figure 11: The regulation signals and their PDFs

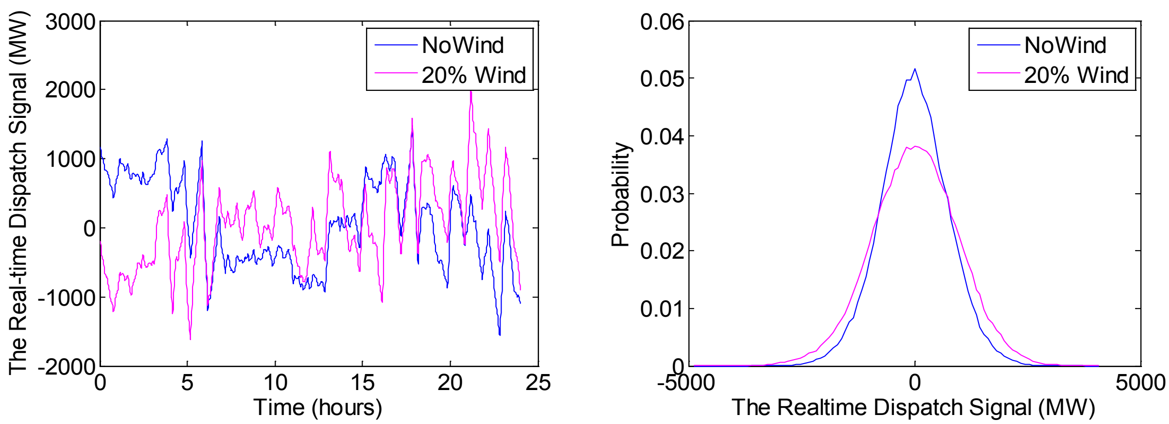


Figure 12: The real-time dispatch signals and their PDFs

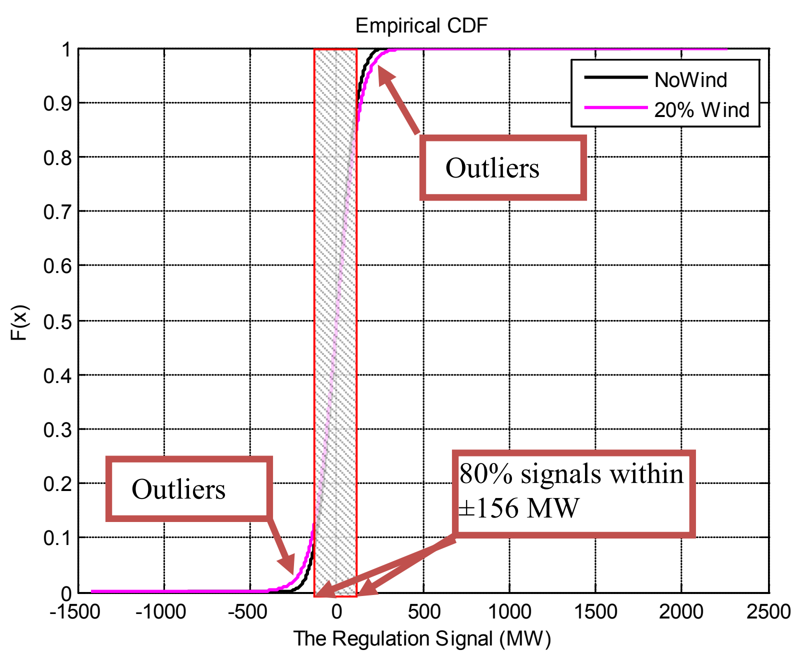


Figure 13: The CDFs of regulation signals

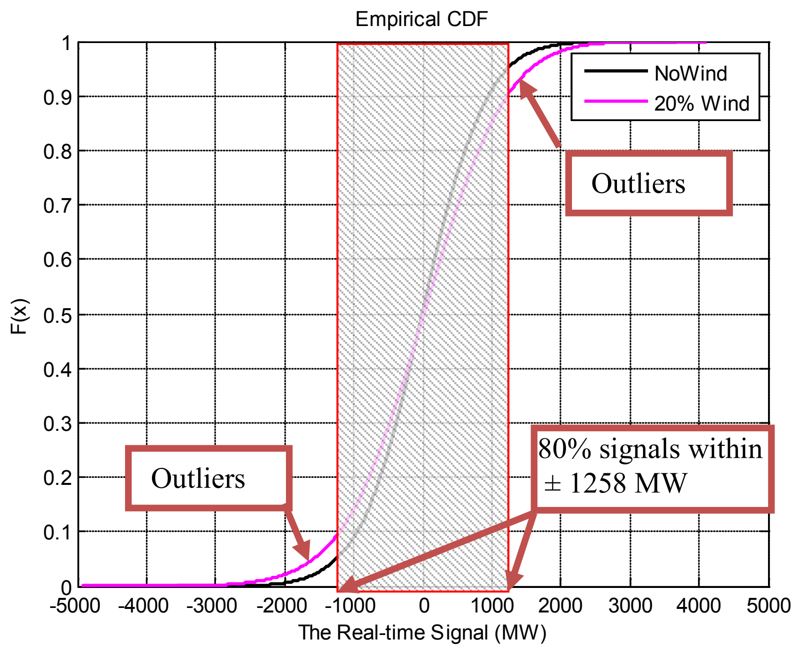


Figure 14: The CDFs of real-time dispatch signals

Table 6: The values to normalize the regulation and real-time dispatch signals

Signals within ±1 MW	95%		90%		80%		50%	
Signals outside ±1 MW	5%		10%		20%		50%	
Case Description	No Wind	20% Renewables	No Wind	20% Renewables	No Wind	20% Renewables	No Wind	20% Renewables
Regulation (MW)	193	248	174	211	137	**156**	83	83
Real-time Dispatch (MW)	1542	1903	1271	1619	1000	**1258**	535	716

2.2.3 Bi-directional and One-directional Services

To provide regulation or real-time dispatch service, an NaS battery can run in either the bi-directional or one-directional mode. In the bi-directional mode, the battery responds to both "up" and "down" signals. In the one-directional mode, the battery responds to "up" signals when it is discharging and "down" signals when charging.

Define the battery utilization rate K_u as:

$$K_u = \frac{P_{ave}}{P_{rated}} \tag{13}$$

or

$$K_u = \frac{E_{annual}^{actual}}{E_{annual}^{\max}} = \frac{P_{ave} \times 24 \times 365}{P_{rated} \times 24 \times 365} \tag{14}$$

where

P_{ave} is the average output of the NaS battery (MW)

P_{rated} is the rated power (MW)

$E_{annual}^{\max}$ is the maximum annual energy provided by the battery (MWh)

E_{annual}^{actual} is the actual annual energy provided by the battery (MWh).

Then, the battery has a 100% utilization rate if charging or discharging at its rated power. If the regulation and real-time dispatch signals vary within the battery rated power, the utilization rates are normally 30-40%, as shown in Table 7.

Table 7: The utilization rates of the NaS Battery when providing bi-directional ancillary services

	Regulation with Wind	Real-time with Wind	Regulation without Wind	Real-time without Wind
Annual Energy (MWh) (At battery rated power 4 MW)	35040	35040	35040	35040
Annual Energy (MWh) (Bi-directional ancillary services)	13245	10893	12948	10376
Maximum Utilization	0.38	0.31	0.37	0.30

There are a few disadvantages to operating the battery to respond to bi-directional signals:

- The battery needs to switch from the charging to discharging mode frequently. This requires complicated control schemes and shortens battery life.
- Because signals are biased in nature, the battery capacity may be depleted from time to time, as shown in Figure 15.

- Because the battery constantly charges and discharges, it is impossible to estimate the battery life from the relationship between the DODs and battery lifecycles.

This study focused on the one-directional service provided by the NaS battery, as shown in Figure 16. The advantages of the one-directional service are:

- The battery is either charging or discharging, so the control mechanism is simple.
- No operation point correction is needed. For example, the battery will switch from providing regulation up services to regulation down services when it reaches the discharging threshold.
- Lifecycles are relatively easy to estimate based on the DODs.

The disadvantages are:

- Lost opportunities. As shown in Figure 17, the battery can only provide either the "up" or "down" service in the one-direction mode but not both at the same time. This results in a revenue loss.
- A reduced utilization rate. At least half of the signals were not responded to. Therefore, the battery sells less energy in the one-direction mode than the bi-directional mode. For example, as shown in Figure 18, a 28 MWh/4MW battery at 100% DOD in the one-directional mode provides 48% regulation energy than it provides in the bi-directional mode. Note that if a battery's cost depends on the capacity but not by the actual energy it supplied, then a reduced utilization rate will not result in revenue losses.

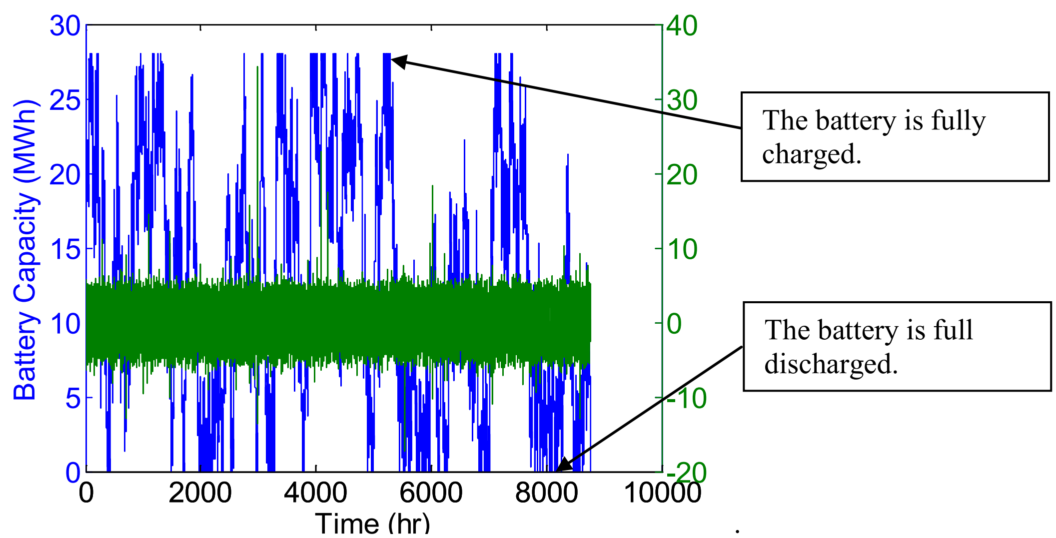


Figure 15: The bi-directional regulation services provided by the 28 MWh/4 MW NaS battery. (Green: the regulation signals normalized to ±4 MW)

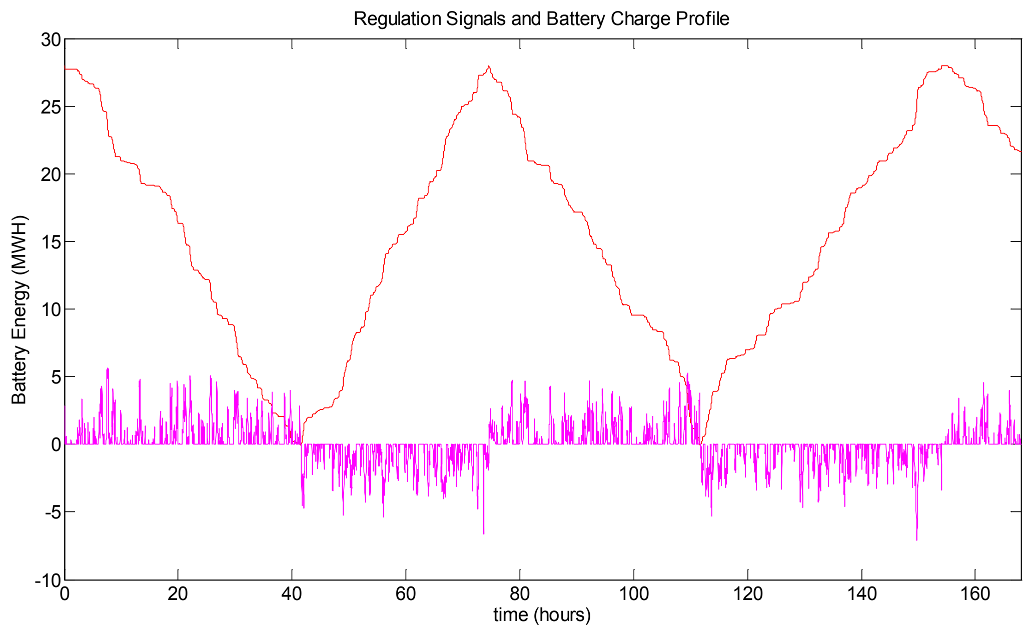


Figure 16: The one-directional service provided by the NaS battery

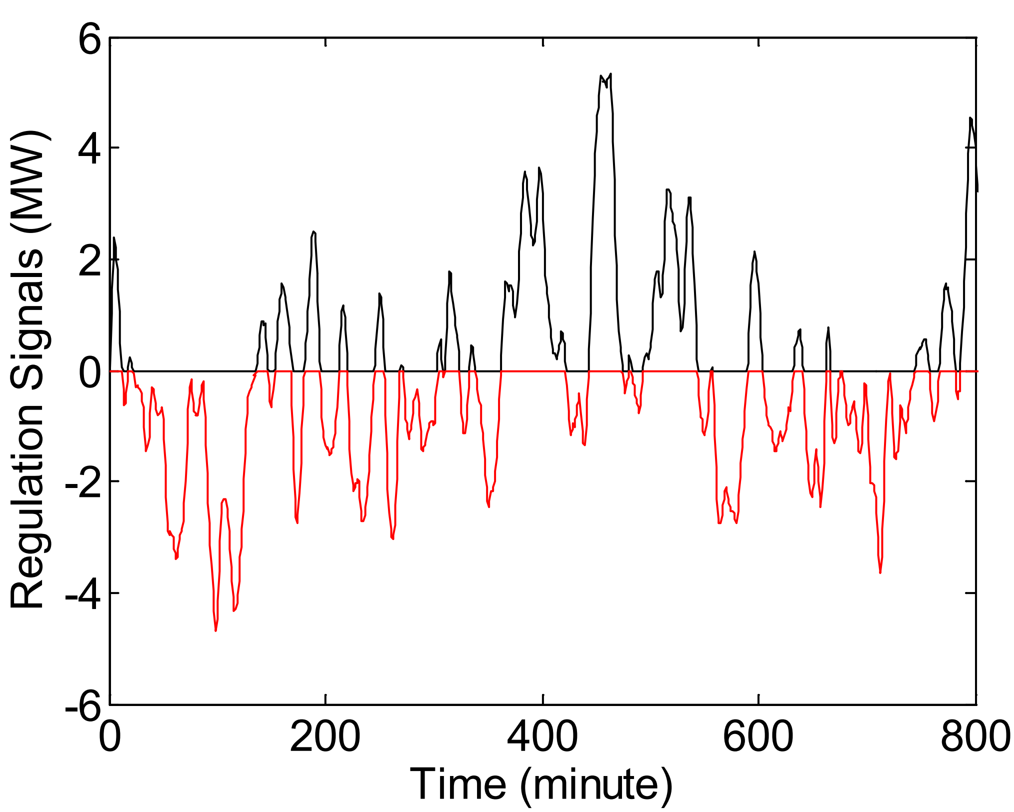


Figure 17: The regulation “up” (black lines) and “down” (red lines) signals

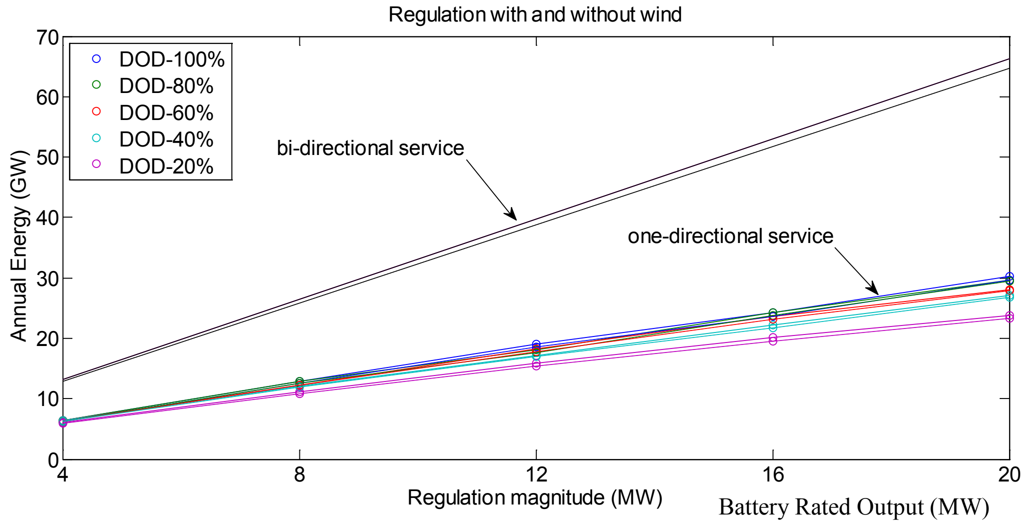


Figure 18: A comparison of bi-directional services and one-directional services provided by the NaS battery (Dotted lines: without wind; Solid lines: with wind)

2.2.4 The Depth of Discharge (DOD)

Operating at different depths of discharge, the NaS battery has different lifecycles. Figure 19 illustrates the charging and discharging profiles of an NaS battery in response to 4 MW regulation signals. Note that the energy the NaS battery provides in a cycle is calculated as:

$$E_{cycle} = 2E_r \times DOD \times \eta \tag{15}$$

The battery lifetime energy is calculated as:

$$E_{lifetime} = E_{cycle} \times L_c \tag{16}$$

The battery lifetime is calculated as:

$$L_y = \frac{L_c}{n_c} \tag{17}$$

where

E_{cycle}	Cycling energy of the battery (MWh)
E_{life}	Lifetime energy (MWh)
E_r	The NaS battery rated capacity (MWh)
L_c	Life (cycle)
DOD	Depth of discharge (DOD)
n_c	Number of charge/discharge cycles in a year

η Efficiency

L_y Life (years)

The lifetime energy provided by an NaS battery at different DODs is plotted out in Figure 20.

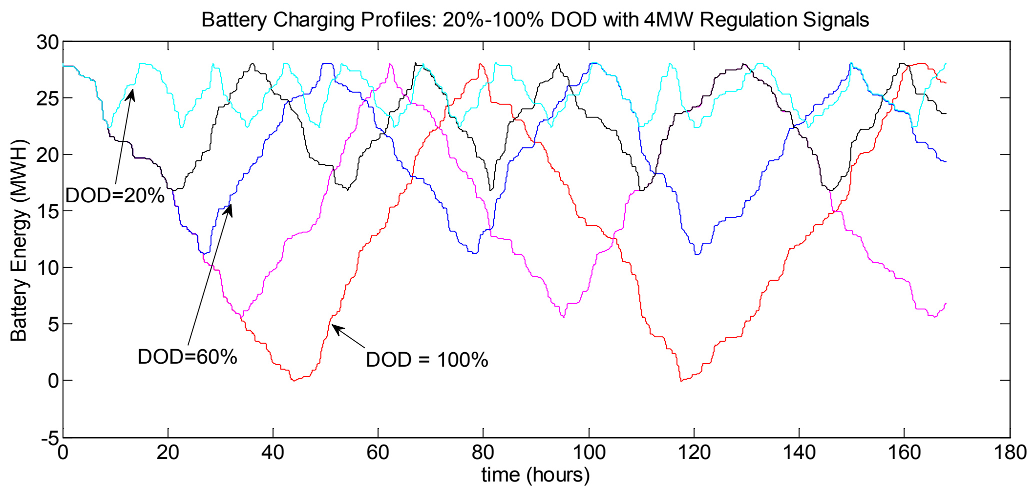


Figure 19: The battery charging and discharging profiles (DOD: 20% - 100%)

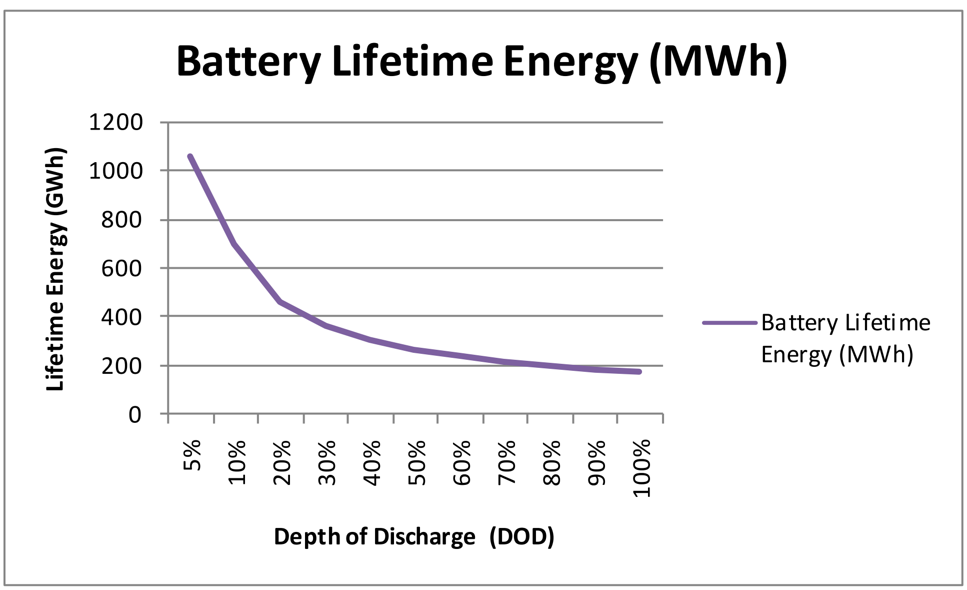


Figure 20: The battery lifetime energy (DOD: 5% - 100%)

2.3 Economic Analysis

In this study, the regulation and real-time dispatch ancillary services were evaluated separately to calculate the price required to breakeven for each service. NPV needs to be evaluated based on all revenue streams available to the battery. This analysis only evaluated the breakeven costs associated with individual services. If future work scope is funded, an analysis that evaluates the multiple services simultaneously will be undertaken and a net present value analysis can be undertaken. Investors primarily look for the NPV of the after-tax cash flows from the investment over its life.

2.3.1 Assumptions

A 4 MW NaS battery bank with a 28 MWh capacity was evaluated. Each ancillary service was evaluated against a simulated CAISO signal and a simulated CAISO signal with 20% of supply being provided by renewable energy resources. In addition, the same battery bank was evaluated at MW power ratings of 8 to 20 MW in 4 MW increments adjusting the capacity for each power rating to maintain the same battery bank. Evaluating the battery bank at different power ratings provides an evaluation of whether higher power ratings could be efficacious under certain circumstances. Thus, four basic analyses were performed- regulation with current CAISO signal and a simulated CAISO with 20 percent renewables, and the same was performed for the real-time dispatch ancillary service.

Regardless of the DOD, it was assumed that the maximum service life of the battery was 20 years. However, at some DODs, primarily 80 and 100 percent with higher MW power ratings, a reduced service life can occur. The analysis used the minimum of the calculated battery life or 20 years [8].

We assumed that the real discount rate was 8 percent, a real rate of return appropriate for a utility. In addition, 7 percent, a discount rate the Office of Management and Budget requires for market analysis was used [9]. The battery bank was assumed to cost $200/kWh based on Walawalker and Apt [8]. A sensitivity case was evaluated based on $150/kWh. At $200/kWh, the 4 MW, 28 MWh battery bank cost $5.6 million. In addition, California sales tax of 8.25% was added to the cost of the battery capital, increasing its total cost to more than $6 million. Operations and maintenance (O&M) costs were estimated at 3 percent of capital costs [8]. A sensitivity case lowered the O&M cost to 1 percent. In addition, the total annual operations costs included a charge of 1% each for property taxes and insurance. Potentially, the efficiency of charge and recharge could affect the O&M cost. However, the cost of energy to the battery was assumed to be $0/kWh as the ancillary service is to provide regulation and real-time dispatch, each of which occur as the battery charges and discharges. If a cost for charging the battery existed, the efficiency of the cycle would have been included. Walawalker and Apt indicated that efficiency of the NaS battery was 75% [8][8]. In our sensitivity study, efficiency was analyzed at 90%, as indicated in Phase I report by Makarov et al [6].

2.3.2 Breakeven Calculation

The breakeven cost assumes that the annualized cost of capital provides an adequate rate of return to the investor. Thus, an 8 percent real rate of return is usually comparable to a nominal 10 to 11 percent rate of return before taxes. The discount rate is usually representative of the entity's weighted cost of capital. Breakeven costs include the annualized cost of capital plus the annual operations and maintenance costs.

Thus the annualized cost of capital including profit before taxes is as follows

$$C_{cap} = \frac{(C_{install} \times (1+i)^n \times i)}{(1+i)^n - 1} \tag{18}$$

where: C_{cap} is the annualized cost of capital
$C_{install}$ is the installed capital cost including sales taxes
i is the discount rate
n is the life of the asset.

$$C_{O\&M} = (k_{op} + k_{pt} + k_{pi}) \times C_{install} + (1-\eta) \times P \tag{19}$$

where: $C_{O\&M}$ is the annual operation and maintenance cost
$C_{install}$ is the installed capital cost
k_{op} is the percent of the installed capital associated with annual O&M
k_{pt} is the percent of the installed capital associated with property tax
k_{pi} is the percent of the installed capital associated with insurance
η is the efficiency of recharge
P is the price of energy in $/kWh.

$$P_{BE} = C_{cap} + C_{O\&M} \tag{20}$$

where: P_{BE} is the breakeven price in $/kWh

2.3.3 NPV Calculation

The NPV calculation evaluates the stream of cash flows from a project using the company's hurdle rate as the discount rate. The hurdle rate is the company's required rate of return on projects. Investments with an NPV greater than 0 indicate that the project has a higher rate of return than the company's hurdle rate.

$$NPV = \sum_{1}^{n} \frac{NCF}{(1+r)^{(n-1)}} \tag{21}$$

where: NPV is net present value
NCF is the annualized net cash flow
r is the entities discount rate
n is life in years of the battery

3.0 Modeling Results

This section presents the modeling results.

3.1 Assumptions

The assumptions are as follows:

- At $t = 0$, the NaS battery is fully charged.
- The battery is always online (charging, discharging, or idling)..
- To provide one-directional services, the NaS battery responds to "**up**" signals when it is **discharging** and "**down**" signals when it is **charging**.
- Battery lifecycles are determined by the DODs, as shown in Table 8.

Table 8: The lifecycles of the NaS battery with respect to the DODs

DOD	5%	10%	20.0%	30.0%	40.0%	50.0%	60.0%	70.0%	80.0%	90.0%	100.0%
Life (Cycles)	379208	125092	41265	21569	13612	9525	7115	5560	4490	3719	3142

- The maximum battery life is 20 years.
- Regulation signals are generated based on 2006 CAISO data. Two cases were considered: 2010 without wind and 2010 with 20% renewables.
- The NaS battery capacity is 28 MWH.
- In the base case, the battery rated power output is 4 MW. Rated power outputs at 8, 12, 16, and 20 MW were also studied to compare the influence of the NaS battery power to capacity ratio.
- The start-up or shut-down costs were not considered.
- Two pairs of parameters were considered in the economic analysis. The high-end and low-end costs are calculated based on Table 9. The breakdown of O&M costs is shown in Table 10. Those costs highlighted in red are the parameters that have different high-end and low-end values.

Table 9: The inputs of the model

Variables	High-end Values	Low-end Values
Maximum Battery Life (yr)	20	20
Discount Rate	0.08	0.07
Capacity (MWh)	28	28
Cost ($/kWh)	200	150
Sales Tax	0.0825	0.0825
Capital Cost ($)	6,062,000	4,546,500
Efficiency	0.75	0.9
Total O&M (% of Capital)	0.05	0.03

Table 10: The breakdown of the total O&M cost

Variables	Values (High End)	Values (Low Ends)
Insurance	0.01	0.01
Property Tax	0.01	0.01
Annual fixed O&M	0.03	0.01
Total O&M (% of Capital)	0.05	0.03

3.2 Fixed Battery Lifetime with Different DODs

The first scenario is the fixed battery lifetime (20 years) study for a 28 MWh battery with rated power output of 4 MW. This study is purely a cost study to show how many cycles a battery needs to run each year at different DODs and how much energy it can provide to the grid if the battery runs for 20 years. It also shows, assuming that the battery is *paid-by-energy*, at what cost the battery owner can breakeven.

3.2.1 Base Case

Note that in this calculation, we do not consider the cost of the energy lost in the charging and discharging process. Therefore, the O&M cost is calculated by letting price $P = 0$ in Equation (19):

$$C_{O\&M} = (k_{op} + k_{pt} + k_{pi}) \times C_{install} + (1-\eta) \times P = (k_{op} + k_{pt} + k_{pi}) \times C_{install} \quad (22)$$

Two breakeven prices are calculated for the high-end and low-end cases: the breakeven prices of 0% and 8% profits with high-end cases and 0% and 7% profits with low-end cases. The DODs are varied from 5% to 100%. The input parameters are shown in Table 9. The costs are calculated based on the method discussed in Section 2.3.2. The breakeven prices are shown in Table 11 and plotted in Figure 21. The battery performance characteristics are calculated by:

$$n_y = \frac{L_c}{L_y} = \frac{L_c}{20} \tag{23}$$

$$n_h = \frac{L_c}{L_y \times 24 \times 365} = \frac{L_c}{20 \times 24 \times 365} \tag{24}$$

$$P_{ave} = 2E_B n_h = 2E_B \frac{L_c}{20 \times 24 \times 365} \tag{25}$$

$$E_{annual} = L_y \times 2E_B \times \eta \tag{26}$$

$$E_{life} = L_c \times 2E_B \times \eta \tag{27}$$

$$K_u = \frac{P_{ave}}{P_{rated}} \tag{28}$$

where

P_{rated}	is the battery rated power (MW)
P_{ave}	is the battery average power output (MW)
E_B	is the battery rated capacity (MWh)
L_c	is the battery life in cycle
L_y	is the battery life in year
n_y	is the number of cycles in 1 year
n_h	is the number of cycles in an hour
k_u	is the utilization factor
η	is the battery efficiency
E_{life}	is the battery lifetime energy (MWh)
E_{Annual}	is the annual energy (MWh).

The calculated battery performance characteristics are shown in Table 12.

Table 11: The cost calculations – base case (fixed lifetime at 20 years)

Base Case With current technology			High End Breakeven Price ($/MWh)		Low End Breakeven Price ($/MWh)	
Life	DOD	Life (cycle)	0% Profit	8% Profit	0% Profit	7% Profit
20	5%	379208	15.22	23.12	7.61	11.84
20	10%	125092	23.08	35.04	11.54	17.94
20	20%	41265	34.98	53.11	17.49	27.19
20	30%	21569	44.61	67.74	22.31	34.68
20	40%	13612	53.02	80.51	26.51	41.22
20	50%	9525	60.61	92.04	30.31	47.12
20	60%	7115	67.62	102.68	33.81	52.57
20	70%	5560	74.17	112.63	37.08	57.66
20	80%	4490	80.36	122.03	40.18	62.48
20	90%	3719	86.24	130.96	43.12	67.05
20	100%	3142	91.87	139.51	45.94	71.43

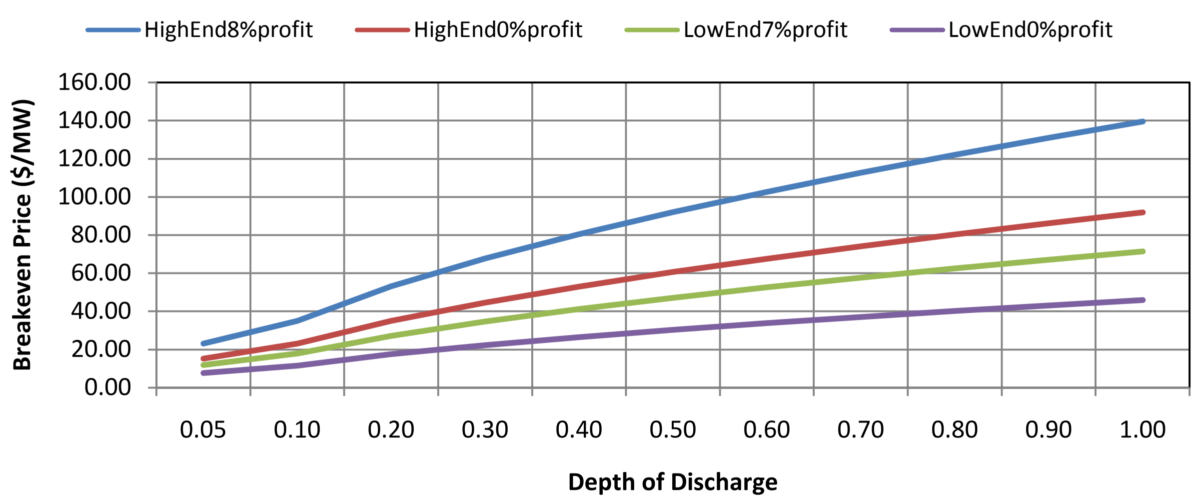


Figure 21: The breakeven prices (fixed lifetime at 20 years)

Table 12: The NaS battery performance characteristics (fixed lifetime at 20 years)

Life (year)	E_B (MWh)	P_{rated} (MW)	DOD	Life (cycle)	cycle/yr	cycle/hr	P_{ave} (MW)	K_u
20.00	28	4	0.05	379208	**18960**	**2.1644**	**4.00**	**1.00**
20.00	28	4	0.10	125092	**6255**	**0.714**	**4.00**	**1.00**
20.00	28	4	0.20	41265	**2063**	**0.236**	**2.64**	**0.66**
20.00	28	4	0.30	21569	**1078**	**0.123**	**2.07**	**0.52**
20.00	28	4	0.40	13612	**681**	**0.078**	**1.74**	**0.44**
20.00	28	4	0.50	9525	**476**	**0.054**	**1.52**	**0.38**
20.00	28	4	0.60	7115	**356**	**0.041**	**1.36**	**0.34**
20.00	28	4	0.70	5560	**278**	**0.032**	**1.24**	**0.31**
20.00	28	4	0.80	4490	**225**	**0.026**	**1.15**	**0.29**
20.00	28	4	0.90	3719	**186**	**0.021**	**1.07**	**0.27**
20.00	28	4	1.00	3142	**157**	**0.018**	**1.00**	**0.25**

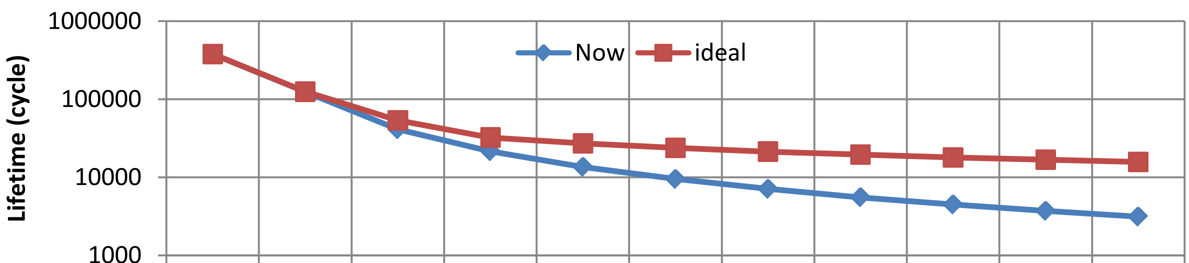
Below are a few observations:

- The breakeven price calculation indicates that the energy price has to be higher than the 0% profit breakeven price for the owner to make a profit. As shown in Table 11, we also studied the case with 7% and 8% profit for the low-end and high-end cases, respectively. Most companies would require at least the 7% return to consider the investment.
- Table 11 and Figure 21 show that if an NaS battery is operated for 20 years at its rated output, operating at a lower DOD results in less cost with the current lifecycle-DOD curve.
- Table 12 shows that at higher DODs, maintaining a fixed battery lifetime of 20 years, the NaS battery must be operated less frequently. As a result, the average power output of the battery is lower. For example, if an NaS battery operates at 10% DOD, it can run at 4 MW and 6255 cycles/year. However, at 100% DOD, the battery can only run at an average output of 1 MW and 157 cycle/year. Thus, if the battery runs at 4 MW and 100% DOD, it will not last 20 years.

3.2.2 Impact of improved lifecycle-DOD characteristics

If lifecycles at higher DODs can be significantly increased (the red line in Figure 22), the breakeven prices will drop significantly when running at higher DODs because more energy will be provided during the 20-year service life. As shown in the dashed lines in Figure 23 and the lower portion of Table 13, running at higher DODs may become cheaper than at lower DODs. As shown in Figure 24, the annual capital cost will drop below $20/MWh, and the annual O&M will drop below $10/MWh at 100% DOD.

Note that when the battery is providing energy services, it can run at a selected constant power output. However, when it responds to ancillary service signals, the signals vary within a range. As shown in Table 7, when providing regulation and real-time dispatch services, an NaS battery runs at 30% to 40% of its rated power output. Therefore, it is only realistic to model the battery performance with regulation and real-time dispatch signals to determine the economics of the battery when providing the ancillary service.



	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Now	379208	125092	41265	21569	13612	9525	7115	5560	4490	3719	3142
ideal	379208	125092	53645	32354	27224	23813	21345	19460	17960	16736	15710

Depth of Discharge

Figure 22: The battery lifecycle curves

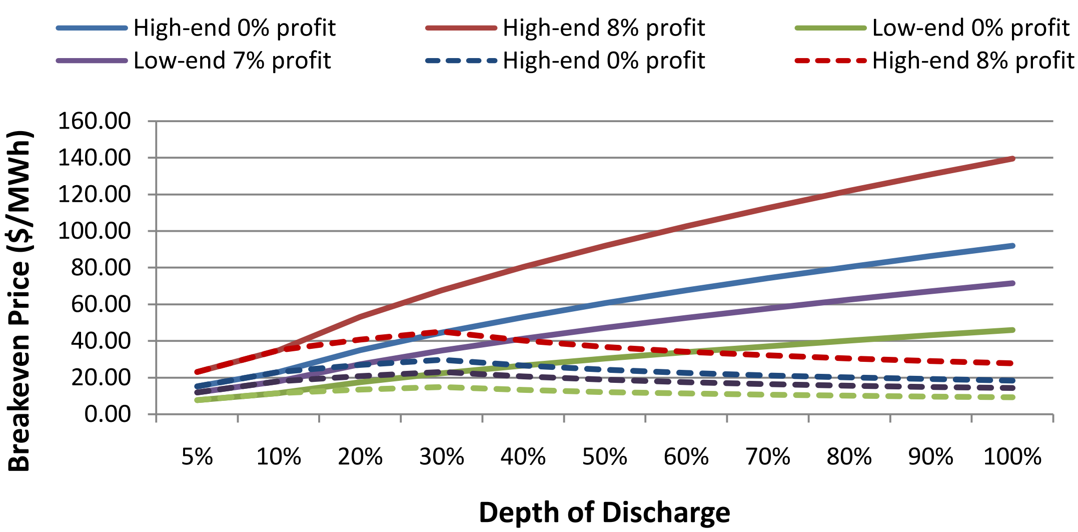
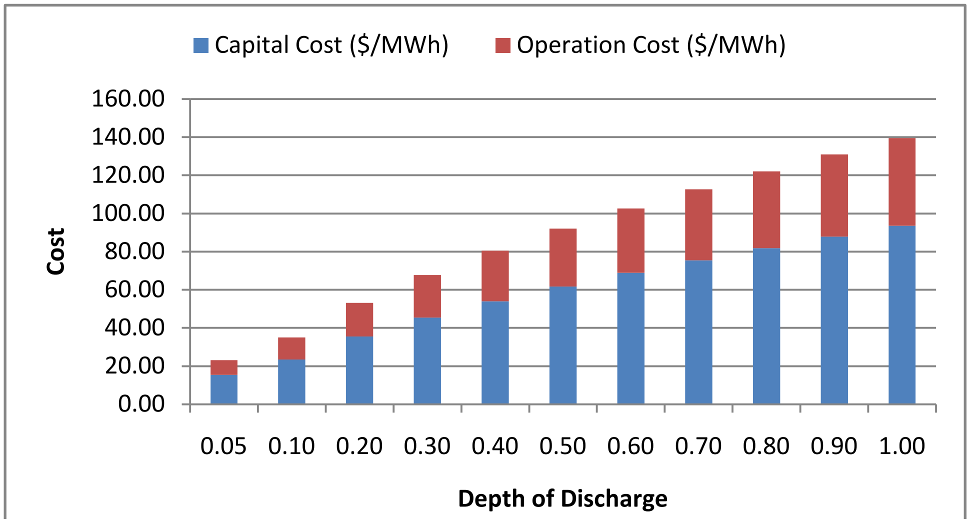


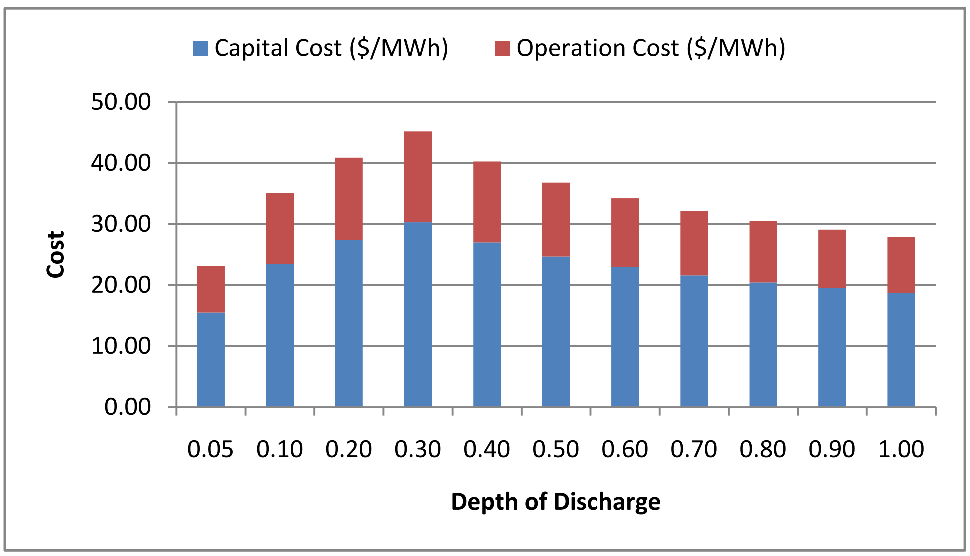
Figure 23: A comparison of high-end and low-end breakeven prices of the improved battery lifecycle case (dashed lines) and the Base case (solid lines)

Table 13: A cost comparison of the base case and the improved lifecycle case

Base Case With current technology			High End Breakeven Price ($/MWh)		Low End Breakeven Price ($/MWh)	
Life	DOD	Life (cycle)	0% Profit	8% Profit	0% Profit	7% Profit
20	5%	379208	15.22	23.12	7.61	11.84
20	10%	125092	23.08	35.04	11.54	17.94
20	20%	41265	34.98	53.11	17.49	27.19
20	30%	21569	44.61	67.74	22.31	34.68
20	40%	13612	53.02	80.51	26.51	41.22
20	50%	9525	60.61	92.04	30.31	47.12
20	60%	7115	67.62	102.68	33.81	52.57
20	70%	5560	74.17	112.63	37.08	57.66
20	80%	4490	80.36	122.03	40.18	62.48
20	90%	3719	86.24	130.96	43.12	67.05
20	100%	3142	91.87	139.51	45.94	71.43
Technology Improvement Prolonged Lifecycles at Higher DODs			High End Breakeven Price ($/MWh)		Low End Breakeven Price ($/MWh)	
Life	DOD	Life (cycle)	0% Profit	8% Profit	0% Profit	7% Profit
20	5%	379208	15.22	23.12	7.61	11.84
20	10%	125092	23.08	35.04	11.54	17.94
20	20%	53645	26.91	40.86	13.45	20.92
20	30%	32354	29.74	45.16	14.87	23.12
20	40%	27224	26.51	40.25	13.25	20.61
20	50%	23813	24.24	36.82	12.12	18.85
20	60%	21345	22.54	34.23	11.27	17.52
20	70%	19460	21.19	32.18	10.60	16.48
20	80%	17960	20.09	30.51	10.05	15.62
20	90%	16736	19.17	29.10	9.58	14.90
20	100%	15710	18.37	27.90	9.19	14.29



(a) Base case: Break-even cost break down



(b) The technology advancement case for prolonged lifecycles

Figure 24: The breakdown of the breakeven price

3.3 Different Regulation and Real-time Dispatch Signals

The second scenario is the different regulation and real-time dispatch signal study. In this case, the total regulation and real-time dispatch signals were normalized with different values, as shown in Table 14, so that there are 5%, 10%, 20%, 30%, and 50% chances for the signal to be outside the range of P_{rated} (±4 MW), as shown in Figure 25. We assume that if the NaS battery receives a regulation signal that is outside ±4 MW, its maximum output will be set at ±4 MW.

The inputs are shown in Table 9. The modeling results are summarized in Table 15 and Table 17, which are color scaled for better visualization. The greener the color is, the better the value. Note that two pairs of values for four inputs have been compared: the discount rate (profits), installation cost, battery efficiency, and the total operation and maintenance (O&M) cost. The high-end and low-end costs of the energy provided for regulation and real-time dispatch services are calculated and presented in Table 16 and Table 17.

Table 14: The values used to normalize the regulation and real-time dispatch signals to 4 MW

Probability of Outliers	5%		10%		20%		30%		50%	
Case Description	No Wind	20%Wind	No Wind	20%Wind	No Wind	20%Wind	No Wind	20%Wind	No Wind	20%Wind
Regulation (MW)	48	62	44	53	34	39	30	34	21	21
Real-time Dispatch (MW)	385	476	318	405	250	314	202	250	134	179

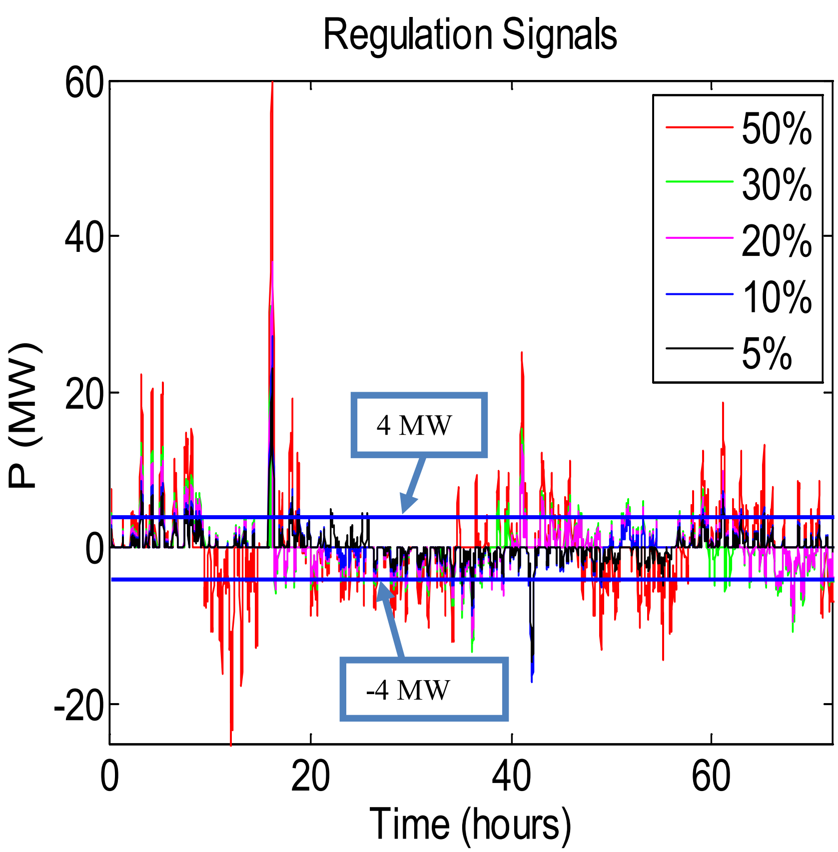


Figure 25: The CDFs of regulation signals

Below are a few observations:

- If the battery does not respond to extreme regulation or real-time dispatch signals, the battery average power output P_{ave} will increase. Normally, the higher P_{ave} is, the more economical the battery service is.

- The study shows that there is no significant difference between "with" and "without" wind cases, when the NaS battery provides the regulation and real-time dispatch services. The annual charge and discharge cycles are similar, as shown in Table 15.

- As shown in Table 16, the breakeven price is positively correlated with the battery utilization rate K_u. A higher utilization results in a lower breakeven price.

- As shown in Table 16, there is a tradeoff between the battery utilization rate K_u and battery lifetime. A higher utilization may result in a shortened battery life. This shortened life occurs because of the limited number of cycles that a battery can run in its lifetime. However, if the battery runs less often at lower DODs, the battery life limitation is not the number of lifecycles but mainly wear-and-tear. In Table 16, the 20 years in green cells are limited by wear-and-tear. In those cases, finding ways to run the battery at a higher utilization rate (a higher average output) would increase profits.

- In Table 17, two cases are compared: high-end cost and low-end cost. If the installation and O&M costs can be reduced, then the breakeven price can be brought down significantly.

Table 15: Number of charge/discharge cycles per year

Annual charge/discharge cycles												
	Signal	DOD						DOD				
	Outliers	1	0.8	0.6	0.4	0.2		1	0.8	0.6	0.4	0.2
Regulation	5%	111	133	179	277	460	Regulation	115	142	189	288	542
20% wind	10%	125	155	207	321	541	No wind	125	159	209	319	591
	20%	159	195	270	369	686		152	190	256	367	701
	30%	172	212	288	383	750		169	209	283	391	763
	50%	219	280	363	491	942		203	255	339	484	921
Realtime	5%	95	115	142	192	288	Realtime	88	109	129	170	257
Dispatch	10%	107	126	160	203	309	Dispatch	101	121	144	192	283
20% Wind	20%	126	151	187	237	356	No Wind	120	136	167	219	323
	30%	145	172	206	269	394		131	150	189	245	351
	50%	164	193	236	305	458		153	187	227	285	411

Table 16: The breakeven prices, utilization rates, and battery lifetimes

		Breakeven Price (8% Profit) ($MWh)					Utilization Rate (Pave/Prated)					Adjusted Lifetime (Year)				
	Signal Outliers	DOD					DOD					DOD				
		1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation	5%	197	206	204	198	238	0.18	0.17	0.17	0.18	0.15	20	20	20	20	20
	10%	175	177	176	171	203	0.20	0.20	0.20	0.21	0.17	20	20	20	20	20
20%	20%	138	140	135	148	160	0.25	0.25	0.26	0.24	0.22	20	20	20	20	20
Renew ables	30%	131	129	127	143	146	0.27	0.27	0.28	0.24	0.24	18	20	20	20	20
	50%	112	105	101	112	116	0.35	0.36	0.35	0.31	0.30	14	16	20	20	20
Real-time	5%	231	238	257	285	381	0.15	0.15	0.14	0.12	0.09	20	20	20	20	20
Dispatch	10%	205	217	228	270	355	0.17	0.16	0.15	0.13	0.10	20	20	20	20	20
	20%	174	181	195	231	308	0.20	0.19	0.18	0.15	0.11	20	20	20	20	20
20%	30%	151	159	177	204	278	0.23	0.22	0.20	0.17	0.13	20	20	20	20	20
renew albes	50%	135	142	155	180	239	0.26	0.25	0.23	0.19	0.15	19	20	20	20	20
Regulation	5%	191	193	193	190	202	0.18	0.18	0.18	0.18	0.17	20	20	20	20	20
No-wind	10%	175	172	175	172	185	0.20	0.20	0.20	0.20	0.19	20	20	20	20	20
	20%	144	144	143	149	156	0.24	0.24	0.25	0.23	0.22	20	20	20	20	20
	30%	132	131	129	140	144	0.27	0.27	0.27	0.25	0.24	19	20	20	20	20
	50%	117	112	108	113	119	0.32	0.33	0.33	0.31	0.29	15	18	20	20	20
Real-time	5%	249	251	283	322	426	0.14	0.14	0.12	0.11	0.08	20	20	20	20	20
Dispatch	10%	217	226	254	285	387	0.16	0.15	0.14	0.12	0.09	20	20	20	20	20
No-wind	20%	183	201	219	250	339	0.19	0.17	0.16	0.14	0.10	20	20	20	20	20
	30%	167	183	193	224	312	0.21	0.19	0.18	0.16	0.11	20	20	20	20	20
	50%	143	147	161	192	267	0.24	0.24	0.22	0.18	0.13	20	20	20	20	20

Table 17: A comparison of breakeven prices

	Signal Outliers	Breakeven Price (High End) DOD 1	0.8	0.6	0.4	0.2	Breakeven Price (Low End) DOD 1	0.8	0.6	0.4	0.2
Regulation	5%	197	206	204	198	238	101	105	104	101	122
	10%	175	177	176	171	203	90	90	90	87	104
20% Renewables	20%	138	140	135	148	160	71	72	69	76	82
	30%	131	129	127	143	146	67	66	65	73	75
	50%	112	105	101	112	116	59	55	52	57	60
Real-time Dispatch	5%	231	238	257	285	381	118	122	132	146	195
	10%	205	217	228	270	355	105	111	117	138	182
	20%	174	181	195	231	308	89	93	100	118	158
20% Renewables	30%	151	159	177	204	278	77	82	91	104	142
	50%	135	142	155	180	239	70	73	79	92	123
Regulation No-wind	5%	191	193	193	190	202	98	99	99	97	104
	10%	175	172	175	172	185	90	88	89	88	95
	20%	144	144	143	149	156	74	74	73	76	80
	30%	132	131	129	140	144	68	67	66	72	74
	50%	117	112	108	113	119	61	58	55	58	61
Real-time Dispatch No-wind	5%	249	251	283	322	426	128	129	145	165	218
	10%	217	226	254	285	387	111	116	130	146	198
	20%	183	201	219	250	339	94	103	112	128	174
	30%	167	183	193	224	312	86	94	99	115	160
	50%	143	147	161	192	267	73	75	82	98	137

3.4 Different Battery Power Ratings

In this scenario, the battery rated power output P_{rated} is assumed to range from 4 to 20 MW. This study evaluates whether or not the operation is more economical when the battery output power is increased. The inputs are shown in Table 9. The regulation and real-time dispatch signals are normalized so that there are 5% signals outside $\pm P_{rated}$, as shown in Figure 26. As shown in Figure 27, at a higher rated power output, the battery can complete more cycles in a fixed time period. The modeling results are summarized in Table 18 and Table 20, which are color scaled for better visualization. The greener the color is, the better the value is.

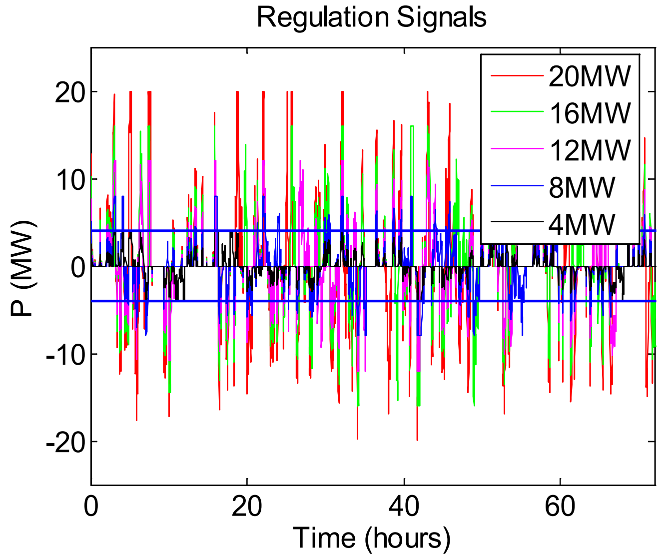


Figure 26: The regulation signals for different NaS battery output ratings

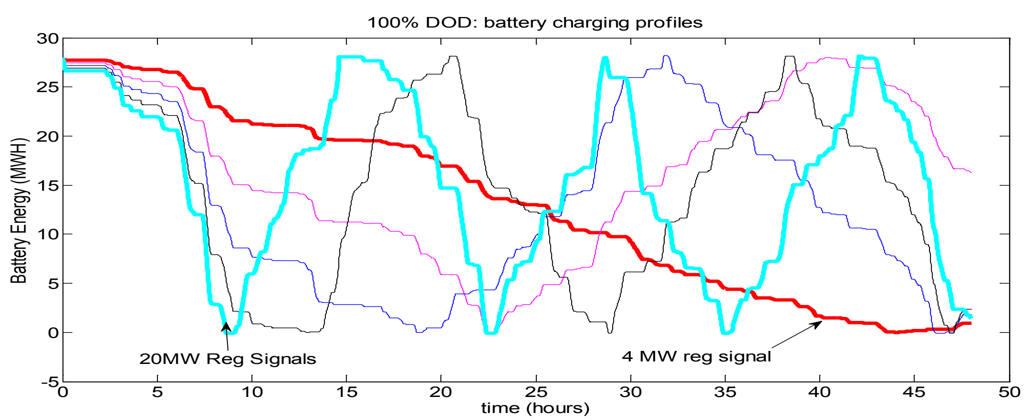


Figure 27: The battery charge/discharge profiles for different NaS battery output ratings

Below are a few observations:

- Increasing the battery's rated power output helps the battery provide regulation services more economically at a lower DOD. As shown in Table 19, the higher the battery's rated power is, the more economical it is for the battery to provide the regulation service at 20% DOD. At a higher rated power output, the battery can complete more cycles in a year, as shown in Table 18. Therefore, more energy will be provided annually, as shown in Figure 28.

- The higher the battery's rated power output, the shorter the battery life is (see Table 19 and Figure 29). Note that the calculated battery lives may exceed 20 years. For those cases, the battery life was limited to be 20 years.

- As shown in Table 19, the higher the battery rated power, the lower the utilization rate K_u. However, the utilization rates and the breakeven prices are no longer positively correlated.

- When considering both the battery lifetime and the economics, the best choice is to run the battery at 20% DOD and 20 MW for regulation and at 60% DOD and 20 MW for real-time dispatch.

- We compared two cases: high-end and low-end costs (see Table 20). As shown in the table, if the installation and O&M cost can be reduced, the breakeven price will drop significantly.

- The battery charging and discharging profiles when providing regulation and real-time dispatch services are shown in Figure 30 and Figure 31. The box plot portrays the battery charging and discharging times at different battery rated-power outputs and DODs when providing regulation and real-time dispatch services (Figure 32 to Figure 35).

- At 4 MW, the DOD does not result in a shortened battery life because the 28 MWh battery is underused when providing regulation services. However, at higher-rated power, there is a tradeoff between DOD and battery life. Therefore, based on the current DOD-lifecycle relationship, if battery manufacturers could increase the battery's rated-power output to 8 or 12 MW, breakeven prices could decline by 1/2 to 2/3. Above 12 MW, the price drop is not significant and the battery life is also shortened dramatically.

Table 18: The annual charge and discharge cycles

Annual charge/discharge cycles												
	P_{rated} (MW)	DOD						DOD				
		1	0.8	0.6	0.4	0.2		1	0.8	0.6	0.4	0.2
Regulation	4	111	133	179	277	460	Regulation	115	142	189	288	542
	8	220	277	355	460	883	No wind	231	288	366	542	989
20%	12	329	368	460	684	1262		337	403	542	772	1416
Renew ables	16	380	460	616	883	1619		432	542	702	989	1790
	20	460	588	762	1076	1933		542	670	853	1230	2132
Real-time	4	95	115	142	192	288	Real-time	88	109	129	170	257
Dispatch	8	163	192	227	288	411	Dispatch	144	170	203	257	356
20%	12	209	238	288	359	525	No Wind	192	216	257	321	453
Renew ables	16	248	288	338	411	623		229	257	298	356	530
	20	288	324	375	467	710		257	285	332	406	602

Table 19: The breakeven prices, utilization rates, and battery lifetimes (different rated battery outputs)

		Breakeven Price (8% Profit) ($MWh)					Utilization Rate (P_{ave}/P_{rated})					Adjusted LifeTime (Year)				
	P_{rated} (MW)	DOD					DOD					DOD				
		1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation 20% Renew ables	4	197	206	204	198	238	0.18	0.17	0.17	0.18	0.15	20	20	20	20	20
	8	112	106	103	119	124	0.18	0.18	0.17	0.15	0.14	14	16	20	20	20
	12	89	89	86	80	87	0.18	0.16	0.15	0.15	0.13	10	12	15	20	20
	16	84	79	73	67	68	0.15	0.15	0.15	0.14	0.13	8	10	12	15	20
	20	77	71	65	60	57	0.15	0.15	0.15	0.14	0.12	7	8	9	13	20
Real-time Dispatch 20% Renew ables	4	164	169	183	203	270	0.15	0.15	0.14	0.12	0.09	20	20	20	20	20
	8	97	101	114	135	189	0.13	0.12	0.11	0.09	0.07	19	20	20	20	20
	12	82	83	90	108	148	0.11	0.10	0.09	0.08	0.06	15	19	20	20	20
	16	74	73	77	95	125	0.10	0.09	0.08	0.07	0.05	13	16	20	20	20
	20	68	68	70	83	110	0.09	0.08	0.07	0.06	0.05	11	14	19	20	20
Regulation No-wind	4	135	137	137	135	144	0.18	0.18	0.18	0.18	0.17	20	20	20	20	20
	8	77	73	71	72	79	0.18	0.18	0.18	0.17	0.16	14	16	19	20	20
	12	63	60	55	52	55	0.18	0.17	0.17	0.16	0.15	9	11	13	18	20
	16	56	52	48	45	43	0.17	0.17	0.17	0.16	0.14	7	8	10	14	20
	20	52	48	44	40	37	0.17	0.17	0.16	0.16	0.14	6	7	8	11	19
Real-time Dispatch No-wind	4	177	179	201	229	303	0.14	0.14	0.12	0.11	0.08	20	20	20	20	20
	8	108	115	128	151	219	0.12	0.11	0.10	0.08	0.06	20	20	20	20	20
	12	86	90	101	121	172	0.10	0.09	0.08	0.07	0.05	16	20	20	20	20
	16	77	79	87	109	147	0.09	0.08	0.07	0.06	0.04	14	17	20	20	20
	20	72	74	78	96	129	0.08	0.07	0.06	0.05	0.04	12	16	20	20	20

Table 20: A comparison of breakeven prices

	P_{rated} (MW)	High-end Breakeven Price ($/MWh) DOD 1	0.8	0.6	0.4	0.2	Low-end Breakeven Price ($/MWh) DOD 1	0.8	0.6	0.4	0.2
Regulation	4	197	206	204	198	238	86	90	89	86	104
	8	112	106	103	119	124	50	47	45	52	54
20%	12	89	89	86	80	87	41	40	38	35	38
Renew ables	16	84	79	73	67	68	39	37	33	30	30
	20	77	71	65	60	57	37	33	30	27	25
Real-time	4	164	169	183	203	270	101	104	112	125	166
Dispatch	8	97	101	114	135	189	59	62	70	83	116
	12	82	83	90	108	148	51	51	55	67	91
20%	16	74	73	77	95	125	47	46	47	58	77
Renew ables	20	68	68	70	83	110	44	43	43	51	67
Regulation	4	135	137	137	135	144	83	84	84	83	88
No-wind	8	77	73	71	72	79	49	46	44	44	48
	12	63	60	55	52	55	41	39	35	32	34
	16	56	52	48	45	43	37	34	31	28	27
	20	52	48	44	40	37	35	32	29	25	23
Real-time	4	177	179	201	229	303	109	110	124	141	186
Dispatch	8	108	115	128	151	219	66	70	79	93	134
No-wind	12	86	90	101	121	172	54	55	62	75	106
	16	77	79	87	109	147	49	49	54	67	90
	20	72	74	78	96	129	46	46	48	59	79

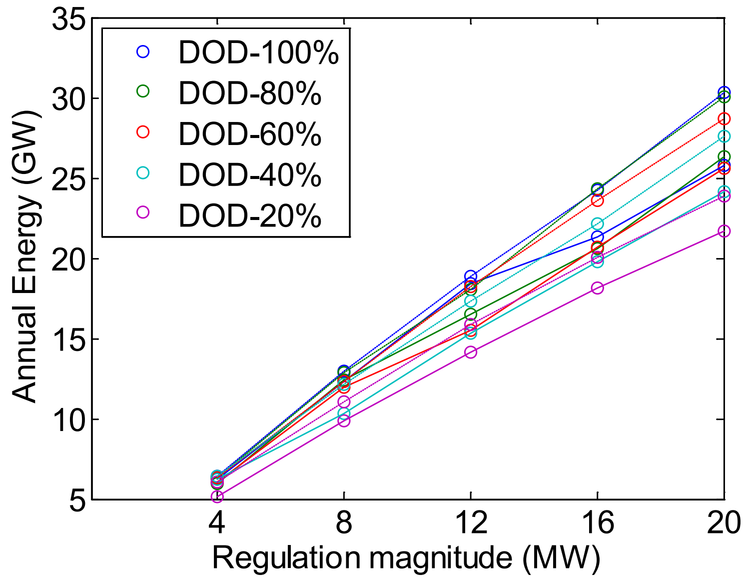


Figure 28: The annual regulation energy provided by battery (dash: without wind, solid: with 20% renewables)

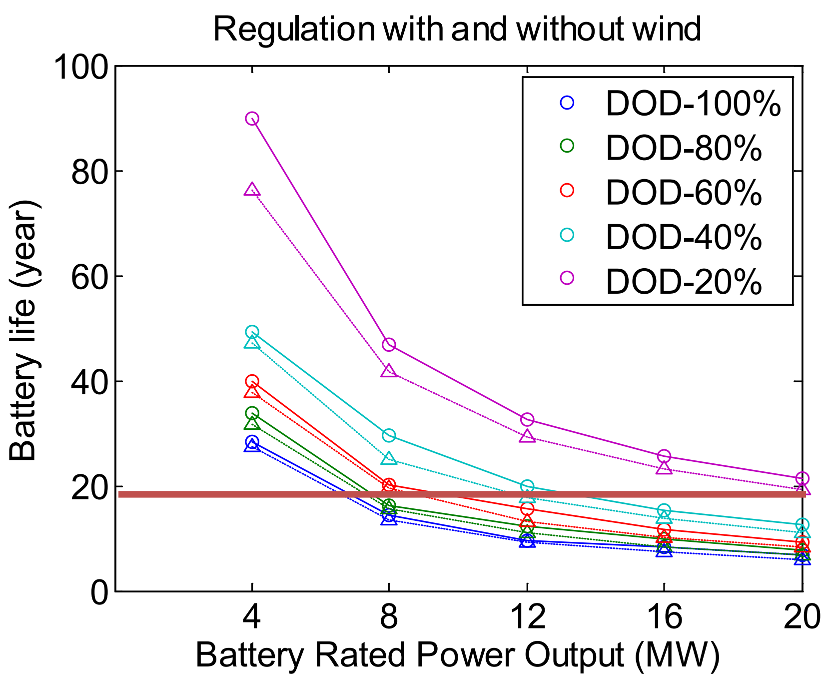


Figure 29: The calculated lifetimes of the NaS battery (solid: with 20% renewables; dash: without wind)

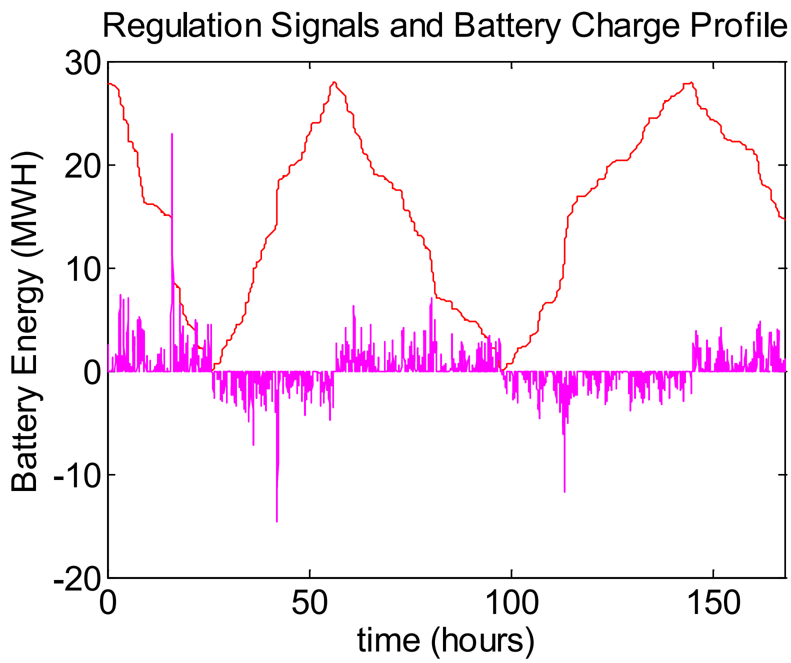


Figure 30: Battery charging/discharging profiles when providing regulation service

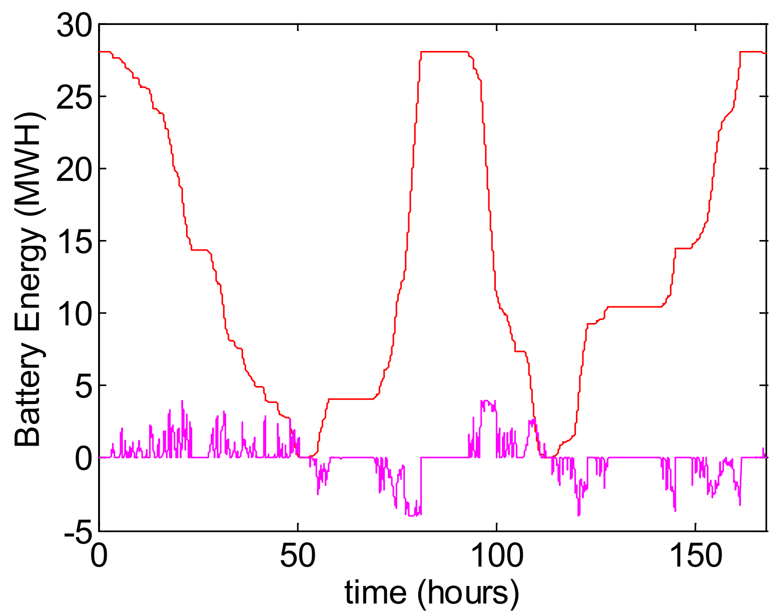


Figure 31: Battery charging/discharging profiles when providing real-time dispatch service

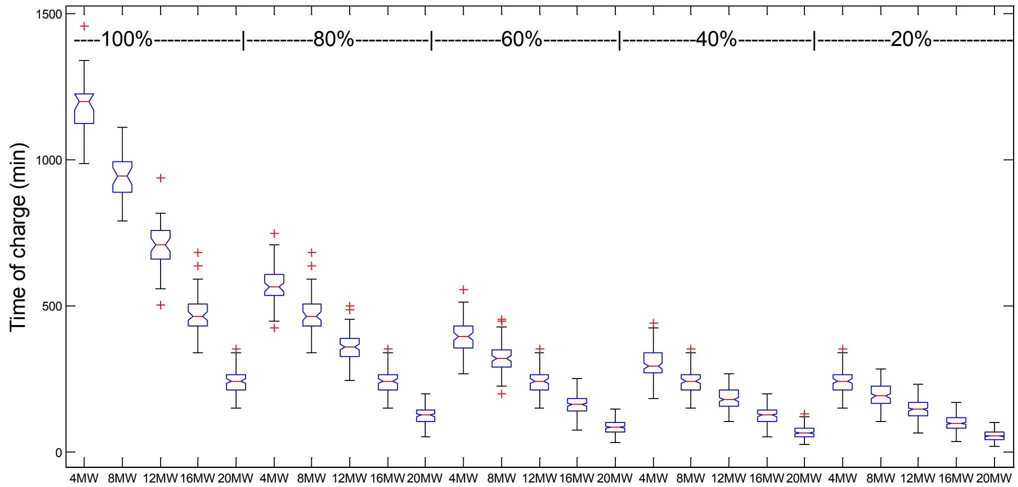


Figure 32: The box plot of battery charging time at different rated power outputs and DODs (regulation)

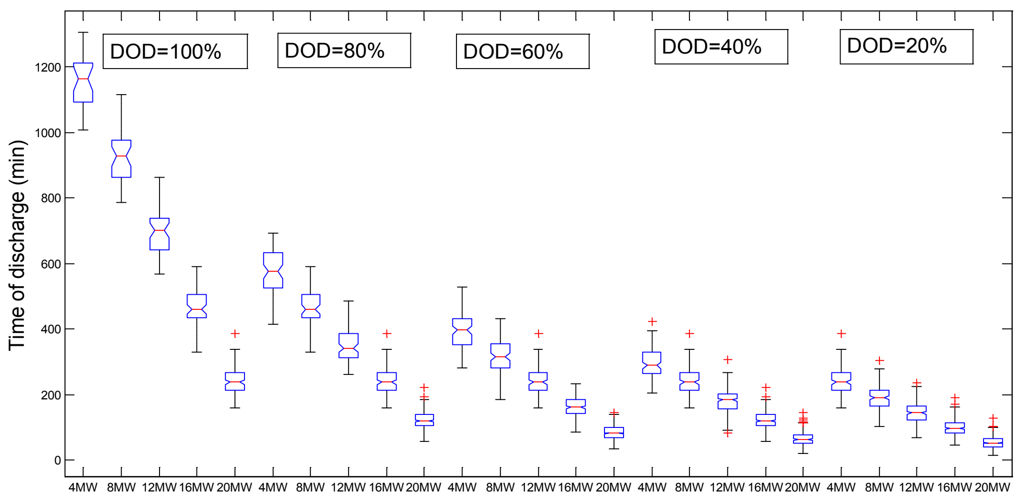


Figure 33: The box plot of battery discharging time at different rated power outputs and DODs (regulation)

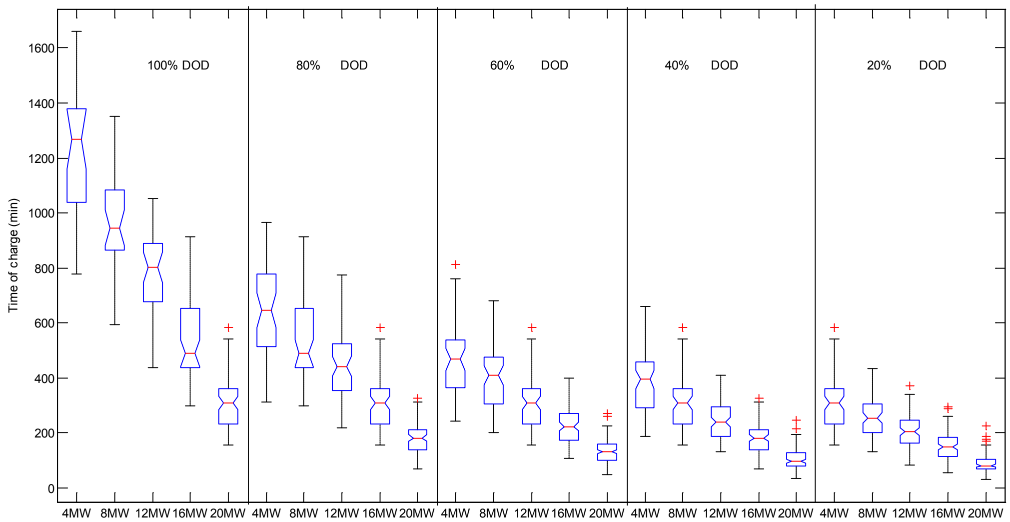


Figure 34: The box plot of battery charging time at different rated power outputs and DODs (real-time dispatch)

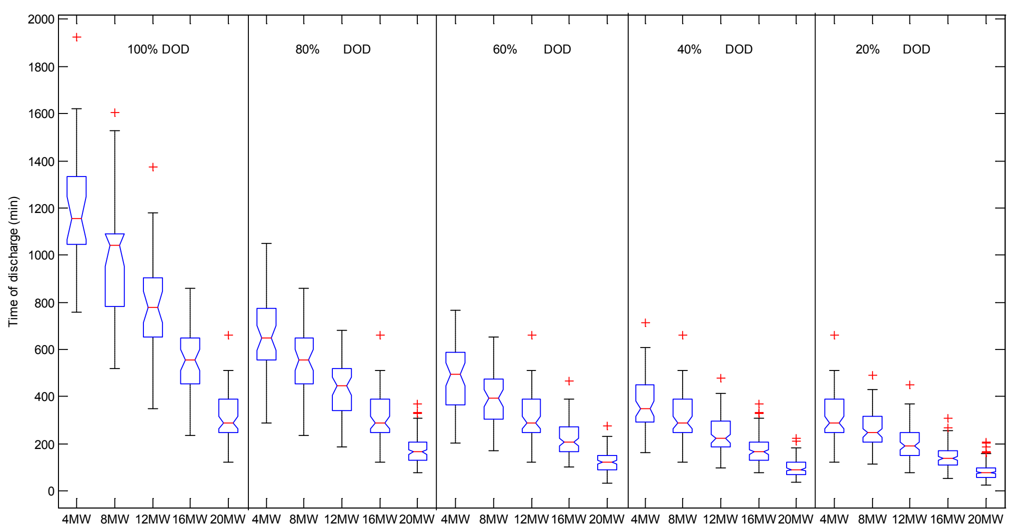


Figure 35: The box plot of battery discharging time at different rated power outputs and DODs (real-time dispatch)

3.5 Different Market Pricing Schemes

So far, the economic study for the regulation and real-time dispatch services provided by the NaS battery is fundamentally a cost-based study. The breakeven price indicates to the battery owner the cost for 1 MWh energy that the battery provides for the regulation and real-time dispatch services. If a battery is *paid-by-energy* provided to the grid, the owner needs to bid into the market with a price equal to or greater than the breakeven price to make expected profits.

In the CAISO market, the real-time dispatch is *paid-by-energy*. However, the regulation service is *paid-by-capacity*. If one bids in 4 MW to the regulation market, then he is paid for 4 MW for the hours that are bid for the service. Even if the battery actually runs at a lower power output during the hour, it still collects the revenue as if it ran at 4 MW for the whole hour.

In this section, the two pricing schemes for regulation are compared for the regulation service provided by the NaS battery: pay-by-energy and pay-by-capacity. Using the simulation results obtained in Section 3.4, an economic analysis was performed on the pay-by-capacity pricing scheme. Note that in the pay-by-energy pricing scheme, the energy is actual energy provided to the grid; in the pay-by-capacity pricing scheme, the energy is the total capacity the battery provides to the grid.

$$\begin{aligned} E_{life}^{actual} &= L_y P_{ave} \times 24 \times 365 \\ E_{life}^{Cap} &= L_y P_{rated} \times 24 \times 365 \end{aligned} \tag{29}$$

where:

E_{life}^{actual} is the actual energy provided in a battery lifetime (MWh)

E_{life}^{Cap} is total capacity the battery provides to the grid in it lifetime (MWh).

With current technology, the battery's rated-power output is 4 MW. As shown in Table 21, if the battery is *paid-by-capacity* in the regulation market, the high-end cost will be $26/MW and the low-end cost will be $16/MW. In the California market, this means that the regulation service provided by the NaS battery may become profitable.

Table 21: The breakeven price comparison between pay-by-energy and pay-by-capacity

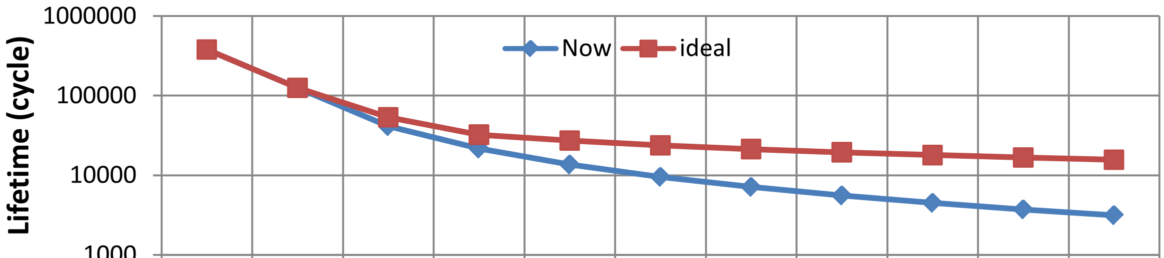
		High-end Pay-by-**Capacity** ($/MW)					Low-end Pay-by-**Capacity** ($/MW)					**Adjusted Life Time (Year)**				
		DOD					**DOD**					**DOD**				
	P_{rated} (MW)	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation 20% Renewables	4	26	26	26	26	26	16	16	16	16	16	20	20	20	20	20
	8	15	14	13	13	13	9	9	8	8	8	14	16	20	20	20
	12	12	10	10	9	9	8	7	6	5	5	10	12	15	20	20
	16	10	9	8	7	7	6	6	5	4	4	8	10	12	15	20
	20	9	8	7	6	5	6	5	5	4	3	7	8	9	13	20
Regulation No-wind	4	26	26	26	26	26	16	16	16	16	16	20	20	20	20	20
	8	15	14	13	13	13	9	9	8	8	8	14	16	19	20	20
	12	12	11	10	9	9	8	7	6	6	5	9	11	13	18	20
	16	10	10	9	7	7	7	6	6	5	4	7	8	10	14	20
	20	9	9	8	7	5	6	6	5	4	3	6	7	8	11	19

		High-end Pay-by-**Energy** ($/MWh)					Low-end Pay-by-**Energy** ($/MWh)					**Adjusted Life Time (Year)**				
		DOD					**DOD**					**DOD**				
	P_{rated} (MW)	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation 20% Renewables	4	197	206	204	198	238	86	90	89	86	104	20	20	20	20	20
	8	112	106	103	119	124	50	47	45	52	54	14	16	20	20	20
	12	89	89	86	80	87	41	40	38	35	38	10	12	15	20	20
	16	84	79	73	67	68	39	37	33	30	30	8	10	12	15	20
	20	77	71	65	60	57	37	33	30	27	25	7	8	9	13	20
Regulation No-wind	4	135	137	137	135	144	83	84	84	83	88	20	20	20	20	20
	8	77	73	71	72	79	49	46	44	44	48	14	16	19	20	20
	12	63	60	55	52	55	41	39	35	32	34	9	11	13	18	20
	16	56	52	48	45	43	37	34	31	28	27	7	8	10	14	20
	20	52	48	44	40	37	35	32	29	25	23	6	7	8	11	19

4.0 Conclusions

The conclusions of the study are summarized as follows:

- If manufacturers can improve the NaS battery lifecycles at high DODs, as shown by the red line in Figure 36, the br eakeven price w ill drop significantly for high DOD c ases. The r esults are compared in Figure 36.



	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Now	379208	125092	41265	21569	13612	9525	7115	5560	4490	3719	3142
ideal	379208	125092	53645	32354	27224	23813	21345	19460	17960	16736	15710

Depth of Discharge

Figure 36: The battery lifetime with respect to the depth of discharge

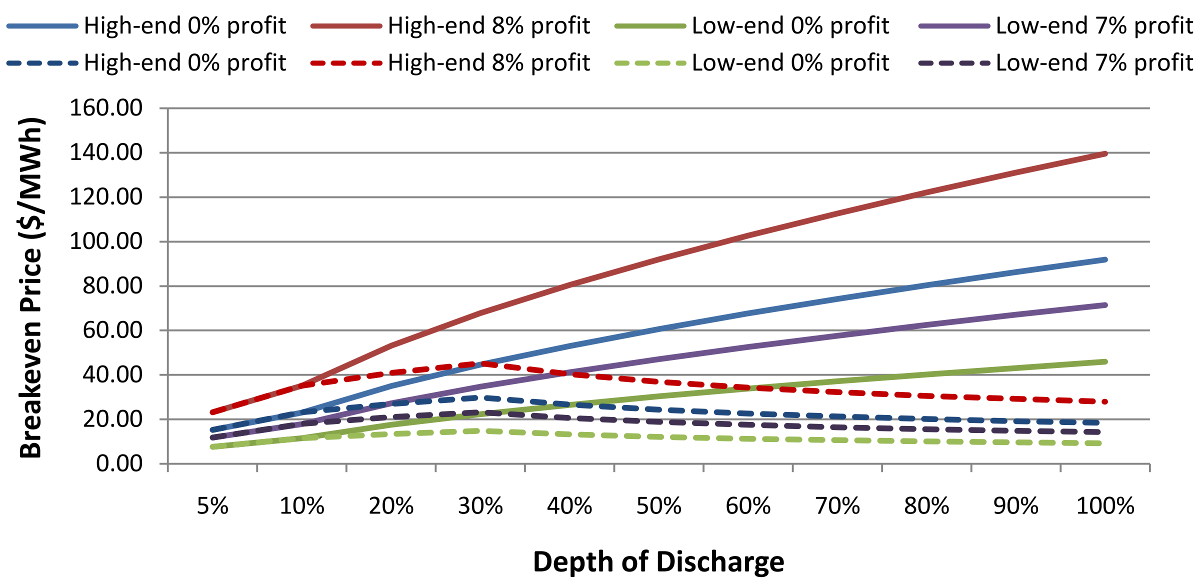


Figure 37: A comparison of high-end and low-end breakeven prices of the improved battery lifecycle case (dashed lines) and the base case (solid lines)

- Under the *pay-by-energy* scheme for regulation and real-time dispatch services breakeven prices are above \$100/MWh, making the operation not economical in the California market, for a 4 MW, 28 MWh NaS battery (see Table 22).

Table 22: The breakeven prices, utilization rates, and battery lifetimes (Pay-by-energy)

	P_{rated} (MW)	Breakeven Price (8% Profit) (\$MWh)					Utilization Rate (P_{ave}/P_{rated})					Adjusted Life Time (Year)				
		DOD					DOD					DOD				
		1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation	4	197	206	204	198	238	0.18	0.17	0.17	0.18	0.15	20	20	20	20	20
	8	112	106	103	119	124	0.18	0.18	0.17	0.15	0.14	14	16	20	20	20
20% Renewables	12	89	89	86	80	87	0.18	0.16	0.15	0.15	0.13	10	12	15	20	20
	16	84	79	73	67	68	0.15	0.15	0.15	0.14	0.13	8	10	12	15	20
	20	77	71	65	60	57	0.15	0.15	0.15	0.14	0.12	7	8	9	13	20
Real-time	4	164	169	183	203	270	0.15	0.15	0.14	0.12	0.09	20	20	20	20	20
Dispatch	8	97	101	114	135	189	0.13	0.12	0.11	0.09	0.07	19	20	20	20	20
	12	82	83	90	108	148	0.11	0.10	0.09	0.08	0.06	15	19	20	20	20
20% Renewables	16	74	73	77	95	125	0.10	0.09	0.08	0.07	0.05	13	16	20	20	20
	20	68	68	70	83	110	0.09	0.08	0.07	0.06	0.05	11	14	19	20	20
Regulation	4	135	137	137	135	144	0.18	0.18	0.18	0.18	0.17	20	20	20	20	20
No-wind	8	77	73	71	72	79	0.18	0.18	0.18	0.17	0.16	14	16	19	20	20
	12	63	60	55	52	55	0.18	0.17	0.17	0.16	0.15	9	11	13	18	20
	16	56	52	48	45	43	0.17	0.17	0.17	0.16	0.14	7	8	10	14	20
	20	52	48	44	40	37	0.17	0.17	0.16	0.16	0.14	6	7	8	11	19
Real-time	4	177	179	201	229	303	0.14	0.14	0.12	0.11	0.08	20	20	20	20	20
Dispatch	8	108	115	128	151	219	0.12	0.11	0.10	0.08	0.06	20	20	20	20	20
No-wind	12	86	90	101	121	172	0.10	0.09	0.08	0.07	0.05	16	20	20	20	20
	16	77	79	87	109	147	0.09	0.08	0.07	0.06	0.04	14	17	20	20	20
	20	72	74	78	96	129	0.08	0.07	0.06	0.05	0.04	12	16	20	20	20

- Under the *pay-by-capacity* scheme for regulation services, the battery has a longer life and a lower cost when it runs at lower DODs (see Table 23). With current technology, the battery's rated power output is 4 MW. The results indicate that if the 4 MW battery provides one-directional regulation service, the high-end cost will be $26/MW and the low-end cost will be $16/MW. In the California market, this means the NaS battery may become marginally profitable.

Table 23: The breakeven price comparison between *pay-by-energy* and *pay-by-capacity*

		High-end Pay-by-**Capacity** (\$/MW)					Low-end Pay-by-**Capacity** (\$/MW)					**Adjusted Life Time (Year)**				
	P_{rated} (MW)	DOD					DOD					DOD				
		1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation	4	26	26	26	26	26	16	16	16	16	16	20	20	20	20	20
	8	15	14	13	13	13	9	9	8	8	8	14	16	20	20	20
20%	12	12	10	10	9	9	8	7	6	5	5	10	12	15	20	20
Renewables	16	10	9	8	7	7	6	6	5	4	4	8	10	12	15	20
	20	9	8	7	6	5	6	5	5	4	3	7	8	9	13	20
Regulation	4	26	26	26	26	26	16	16	16	16	16	20	20	20	20	20
No-wind	8	15	14	13	13	13	9	9	8	8	8	14	16	19	20	20
	12	12	11	10	9	9	8	7	6	6	5	9	11	13	18	20
	16	10	10	9	7	7	7	6	6	5	4	7	8	10	14	20
	20	9	9	8	7	5	6	6	5	4	3	6	7	8	11	19

		High-end Pay-by-**Energy** (\$/MWh)					Low-end Pay-by-**Energy** (\$/MWh)					**Adjusted Life Time (Year)**				
	P_{rated} (MW)	DOD					DOD					DOD				
		1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation	4	197	206	204	198	238	86	90	89	86	104	20	20	20	20	20
	8	112	106	103	119	124	50	47	45	52	54	14	16	20	20	20
20%	12	89	89	86	80	87	41	40	38	35	38	10	12	15	20	20
Renewables	16	84	79	73	67	68	39	37	33	30	30	8	10	12	15	20
	20	77	71	65	60	57	37	33	30	27	25	7	8	9	13	20
Regulation	4	135	137	137	135	144	83	84	84	83	88	20	20	20	20	20
No-wind	8	77	73	71	72	79	49	46	44	44	48	14	16	19	20	20
	12	63	60	55	52	55	41	39	35	32	34	9	11	13	18	20
	16	56	52	48	45	43	37	34	31	28	27	7	8	10	14	20
	20	52	48	44	40	37	35	32	29	25	23	6	7	8	11	19

- The breakeven price will drop significantly if the battery's rated-power output can be increased (Table 22, Table 23 and Figure 38) because the battery is able to handle a broader range of signals. However, above 12 MW, the price decline is not significant, but the battery life is shortened dramatically. Therefore, if battery manufacturers increase the battery's rated-power output up to 8 or 12 MW breakeven price could decline 1/2 to 2/3 based on the current lifecycle-DOD curve.

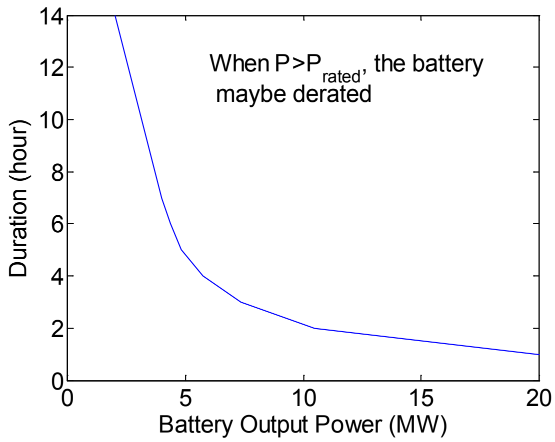


Figure 38: The 28 MWh NaS battery capacity to power ratio

- At higher-rated power, there is a tradeoff between the depth of discharge (DOD) and battery life (see Table 22 and Table 23). At 4 MW, the DOD does not result in a shortened battery life because the 28 MWh battery is underused when providing the regulation. At 20 MW, however, the battery lives are significantly shorter at higher DODs.

- The NaS battery provides almost the same amount of regulation or real-time dispatch services for the "with 20% renewables" and "without wind" cases. Thus, the breakeven prices were similar. More batteries contribute greater ancillary service capacity and therefore, allow more intermittent generation resources to connect to the power grid. However, the amount of regulation and real-time dispatch services that an individual battery provides depends mainly on its power rating. For the "with 20% renewables" and "without wind" cases, signals sent to the NaS battery are all within its rated power output ±4 MW. For example, although 193 MW are needed for regulation without wind, and 248 MW are needed for regulation with 20% renewable, for the 4 MW NaS battery, it provides services within ±4 MW in both cases; therefore, the amounts of energy provided in both cases are similar.

- The regulation and real-time dispatch signals sent to the NaS battery are scaled total regulation and real-time dispatch signals, so that the signals are within the battery rated power output, for example, ±4 MW. As shown in Figure 39, for the case in which 50% of the time, the normalized signal is outside ±4MW, the battery average power output is much higher than that of the 5% case, resulting in more economical services (see Table 24). For the 50% of signals outside the battery's capability, the regulation and real-time signals can be provided more efficiently by storage devices that have high power outputs but less energy storage capacities, for example, flywheels.

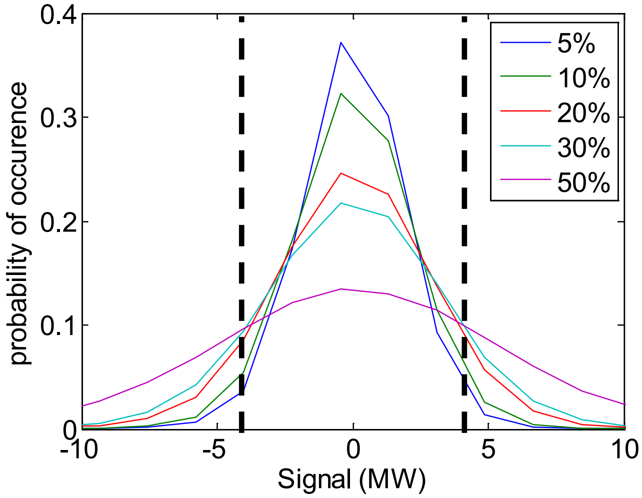


Figure 39: The probability distribution functions of the regulation signals

Table 24: A comparison of breakeven prices for different normalized signals

		Breakeven Price (High End)					Breakeven Price (Low End)				
	Signal	DOD					DOD				
	Outliers	1	0.8	0.6	0.4	0.2	1	0.8	0.6	0.4	0.2
Regulation	5%	197	206	204	198	238	101	105	104	101	122
	10%	175	177	176	171	203	90	90	90	87	104
20%	20%	138	140	135	148	160	71	72	69	76	82
Renewables	30%	131	129	127	143	146	67	66	65	73	75
	50%	112	105	101	112	116	59	55	52	57	60
Realtime	5%	231	238	257	285	381	118	122	132	146	195
Dispatch	10%	205	217	228	270	355	105	111	117	138	182
	20%	174	181	195	231	308	89	93	100	118	158
20%	30%	151	159	177	204	278	77	82	91	104	142
Renewables	50%	135	142	155	180	239	70	73	79	92	123
Regulation	5%	191	193	193	190	202	98	99	99	97	104
No-wind	10%	175	172	175	172	185	90	88	89	88	95
	20%	144	144	143	149	156	74	74	73	76	80
	30%	132	131	129	140	144	68	67	66	72	74
	50%	117	112	108	113	119	61	58	55	58	61
Realtime	5%	249	251	283	322	426	128	129	145	165	218
Dispatch	10%	217	226	254	285	387	111	116	130	146	198
No-wind	20%	183	201	219	250	339	94	103	112	128	174
	30%	167	183	193	224	312	86	94	99	115	160
	50%	143	147	161	192	267	73	75	82	98	137

Future research should focus on the economics of the combined services of batteries. By bidding into the energy, regulation, real-time dispatch, and reserve markets, the battery owner can collect revenue from different markets, likely resulting in a more economical operation than bidding in a single market. However, providing multiple services requires an optimization on the battery's commitment schedule. To address these optimal operation strategies, a battery commitment problem needs to be well defined and solved.

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